HEAD-MOUNTED DISPLAYS AND DYNAMIC TEXT PRESENTATION TO AID READING IN MACULAR DISEASE

Howard Farnoush Freemantle Moshtael-Oskui

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School of Engineering & Physical Sciences

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ABSTRACT

The majority of individuals living with significant sight loss have residual vision which can be enhanced using low vision aids. Smart glasses and smartphone-based headsets, both increasing in prevalence, are proposed as a low vision aid platform. Three novel tests for measuring the visibility of displays to partially sighted users are described, along with a questionnaire for assessing subjective preference. Most individuals tested, save those with the weakest vision, were able to see and read from both a smart glasses screen and a smartphone screen mounted in a headset. The scheme for biomimetic scrolling, a text presentation strategy which translates natural eye movement into text movement, is described. It is found to enable the normally sighted to read at a rate five times that of continuous scrolling and is faster than rapid serial visual presentation for individuals with macular disease. With text presentation on the smart glasses optimised to the user, individuals with macular disease read on average 65% faster than when using their habitual optical aid. It is concluded that this aid demonstrates clear benefit over the commonly used devices and is thus recommended for further development towards widespread availability.

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CONTENTS

GLOSSARY

AMD: Age-related macular degeneration

CFL: Central field loss

CRT: Cathode ray tube

FoV: Field of view

GUI: Graphical user interface

HDTV: High definition television

HMD: Head-mounted display

LED: Light emitting diode

LV: Low vision

LVA: Low vision aid

PRL: Preferred retinal locus

RSVP: Rapid serial visual presentation

TFT: Thin film transistor

TRL: Trained retinal locus

PUBLICATIONS

"Dynamic text display on smart glasses as a novel low vision reading aid," H. Moshtael, A. Nuthmann, I. Underwood, B. Dhillon, *[To be submitted]*

"A text display method and apparatus," H. Moshtael, B. Dhillon, I. Underwood, A. Nuthmann, UK Patent Application No. 1615382.7, filed 9 September 2016.

"Saccadic Scrolling: Speed Reading Strategy Based on Natural Eye Movements," H. Moshtael, A. Nuthmann, I. Underwood, B. Dhillon, 8th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), pp. 596-600 (IEEE, 2016).

"Evaluation of Head-Mounted Displays for Macular Degeneration: A Pilot Study," H. Moshtael, L. Fu, I. Underwood, B. Dhillon, Innovation in Medicine and Healthcare 2016, Volume 60 of Smart Innovation, Systems and Technologies, pp. 71-81 (Springer, 2016).

"Quantifying the Ability of Individuals with Macular Disease to See and Read Content on Virtual and Augmented Reality Devices," H. Moshtael, L. Fu, I. Underwood, B. Dhillon, Proceedings from SID EuroDisplay 2015, Ghent, Belgium (2015).

"High Tech Aids Low Vision: A Review of Image Processing for the Visually Impaired," H. Moshtael, T. Aslam, I. Underwood, B. Dhillon, Translational Vision Science & Technology, 4, 6 (2015).

CONFERENCE PRESENTATIONS

“Saccadic Scrolling: Speed Reading Strategy Based on Natural Eye Movements,” Oral presentation at IEEE 8th International Conference on Intelligent Human-Machine Systems and Cybernetics, 10-11 Sept 2016, Hangzhou, China.

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“The potential for head-mounted displays as low vision aids,” Invited talk at 15th EURETINA Congress, 17-20 Sept 2015, Nice, France.

CHAPTER 1

Introduction

1.1 Introduction

Of our five senses, vision is the most significant, accounting for some 40% of our sensorial input [1]. Naturally then, damage to this sense has considerable impact on the ability to perform daily tasks and can lead to a significant reduction in the person's quality of life. There are an estimated 1.86 million people living in the UK with "sight loss that has a significant impact on their daily lives" [2]. The severity of sight loss is a continuum upon which markers are set to define "blindness" and "low vision". The definitions vary across institutions but are generally based upon visual acuity and field loss.

The ratio of blind to low vision suffers in Europe is about 1:10 according to a report by the World Health Organization [3]. Thus the majority of those with significant sight loss still possess some useable vision. Low vision rehabilitation seeks to assist them to make the best use of this vision. This may be as simple as ensuring there is sufficient illumination, but usually involves the use of a low vision aid and/or coping strategy.

For decades, the optical magnifier has been the mainstay of visual rehabilitation. Its magnifying power, field of view and viewing distance have, however, been surpassed by electronic magnifiers [4]. But beyond the mere electronification of standard techniques, the advances in display technology and the miniaturization of electronics has opened the door to more sophisticated solutions.

Head-mounted display systems have recently gained exposure in the consumer market through virtual reality devices and smart glasses. This thesis asks how visible and acceptable these displays are to those with macular disease. It then investigates the optimisation of text presentation on these displays, tailored to the needs of individuals. In sum, the basis for a novel low vision reading aid is established.

1.2 Thesis structure

The initial step is to review the literature to identify the past and current approaches to assisting reading. The introductory chapter gives the background to the two optical instruments most central to the research described in subsequent chapters – the human eye and the head-mounted display. Regarding the human eye: The operation and key parameters of the eye are outlined as well as the most common means for the measurement of eyesight; the eye diseases that most commonly lead to irreparable sight loss are then described; finally, the visual requirements for reading, both in terms of eyesight and the appearance of text, are discussed. The head-mounted display is considered in the context of low vision aids: The main approaches to visual rehabilitation and low vision aids are first discussed; the head-mounted display is then described before reviewing the literature on its use in low vision aids.

Moving from hardware to software, Chapter 2 is a review of studies that utilise digital image processing to enhance the visual potential of the partially sighted. The studies are categorised according to the image processing technique used and their effects on vision are summarised. The manipulation of both images and text is considered. The differences in the levels of processing suitable for normally sighted and partially sighted individuals are compared, and a discussion made on the various experimental designs and methods of evaluation.

In addition to consulting the literature to inform the development process, the end users – those suffering from macular disease – are assessed and consulted. This is done using objective and subjective measures respectively, as reported in Chapter 3. The methodology for this patient trial is outlined, and the two head-mounted displays selected for study are presented. In order to measure the visibility of the screens to individual users, in terms of contrast, spatial extent and reading speed, screen visibility tests are developed based on standard vision tests. These results are presented alongside the results of a questionnaire to gain user feedback. The implications of these results are discussed for the visibility of the screens, for how the screens compare to each other and to large print, and for the screen visibility tests themselves.

Having assessed the displays, Chapter 4 turns to the question of how to present text on them. A review is made of the methods for dynamically presenting text, and of the studies that investigated their effect on the partially sighted. Based on the findings of this review, a novel approach to text presentation is described which is based on the psychological theory of ocular motion. This approach firstly involves analysing the trends in the eye movement data in order to determine mathematical relations between text characteristics and the manner in which the text is read. The text is then moved across the screen with the characteristics of eye movements. The parameters required to define this text movement are outlined and a particular configuration of these parameters is suggested. Finally, a reading speed study with normally sighted participants is presented to compare the new method of text presentation with three other methods.

The findings about head-mounted displays and text presentation from the previous chapters come together in Chapter 5 in the development of a novel aid to reading in macular disease. The features of the app that is used on the smart glasses are presented, as are the methods of text presentation used to optimise the display for the user. The methodology for a patient study is described and the results for each of the features of the reading aid are presented and discussed. This reading aid, with the text presentation tuned to the needs and preferences of each user, is compared to the most commonly used reading aid, the optical magnifier.

The final chapter presents the conclusions of the thesis, its potential impact, and the new avenues of research that it opens up.

1.3 Low vision

1.3.1 The human eye

The role of the eye in the sense of sight is to transfer visual information, contained in the light reflected or emitted from objects, to the brain. The eye itself does not have the distinction of doing the seeing, as is evidenced by the condition of amblyopia where it can be perfectly healthy but, due to the requisite part of the brain being underdeveloped, of minimal use to vision.

Thus the eye can be understood, from one perspective, as a biological optical instrument with parameters including resolution, colour discernment, signal frequency, minimum and maximum brightness, and field of view. To give an indication of the range of these parameters, Table 1.1 summarises their approximate values. The values depend heavily on factors such as brightness, contrast and spatial or temporal frequency of the image but are included to give an indication of the potential of the eye under optimal conditions. What we learn about the eye from this data is that it has a huge dynamic range, being sensitive enough to detect from just a few photons with scotopic sight, to around 11 orders of magnitude higher with photopic sight.

Table 1.1: Some key performance parameters of the human eye and their values [4].

Angular resolution of fovea	1 arcminute,
Range of wavelengths discernible	380 nm (violet) to 780 nm (red)
Maximum signal frequency discernible	30 Hz
Minimum radiance detectable	10^{-6} cd/m^2 (A few photons)
Maximum radiance acceptable	10^5 cd/m^2
Minimum illuminance difference distinguishable	10^{-9} Lux
Field of view - maximum	108° (nearly 180° for both eyes together)
Field of view - fovea	5.5°
F-number	6.8 to 2.4

Figure 1.1 shows a sketch of the main components of the eye that are directly involved in the transfer of visual information to the brain. They can be divided into the adjustable aperture, the focusing elements and the photoreceptive elements.

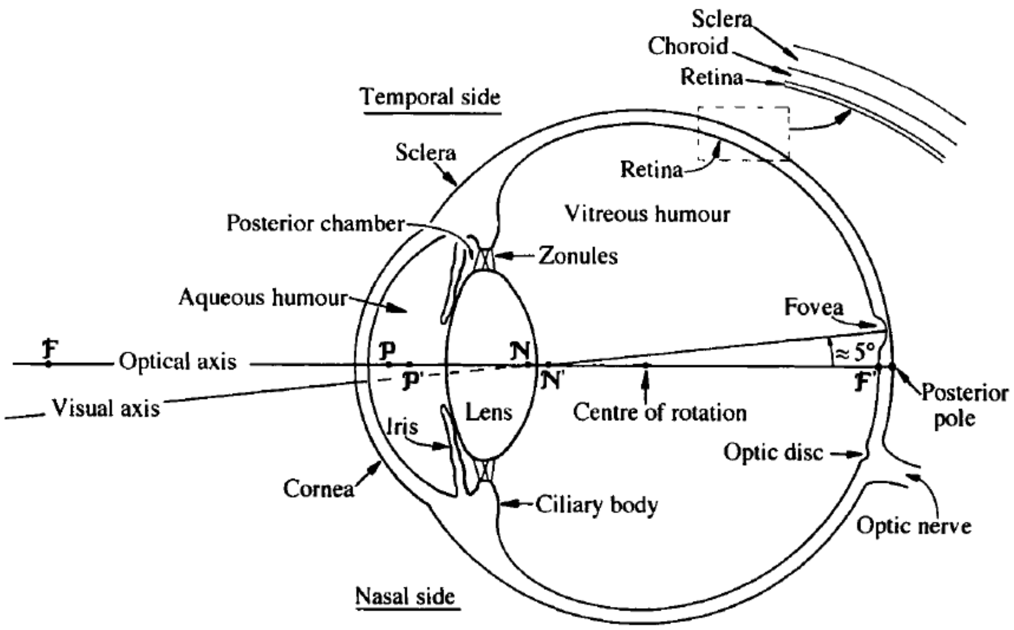

Figure 1.1. A horizontal section of the right eye at its widest point as seen from above, showing the principal components to vision. The pupil is the opening in the centre of the iris. Reprinted from [6] with permission from Elsevier.

Light enters the eye through the pupil, the gap in the iris which acts as the aperture of the optical system. The iris is made of muscle and the size of the pupil is adjusted through its contraction and retraction. The diameter of the pupil is inversely proportional to the radiance of light entering it. This mechanism is the primary way the eye adapts to ambient light conditions; it is rapid and governs the range from 10^2 to 10^4 cd/m^2. Below this, when performing dark adaption, a chemical process is used to increase the sensitivity of the photoreceptors, the rods and cones: Over the first seven minutes new pigment is generated for the cones, then for the following 30 minutes rhodopsin is generated for the rods [5].

When light from an object enters the eye it must be focussed onto the retina. This is performed in a partnership between the cornea and the crystalline lens. The greatest change in refractive index occurs at the air-cornea interface, going from 1 to 1.377. Thus it is the cornea that has the greatest refractive power and accounts for two thirds of the total refractive power of the eye (in air). The remaining third is given by the crystalline lens which has an average refractive index of 1.41 [5]. However, it is only the lens that is adjustable and allows accommodation of light coming from any distance between infinity and about 7 cm.

In normal vision the focal length of the eye's optical system is adjusted such that the incoming light is focused onto the retina. This process is called accommodation. If the light rays come to a focus in front of the retina, when the eyeball is too long for example, then images at a distance appear blurred. This is called myopia, or short-sightedness. The opposite condition, hyperopia or long-sightedness, is when the light rays come to a focus behind the retina and only distant images appear sharp. The condition of the refractive power of the eye being different in the horizontal and vertical directions is called astigmatism [7].

Lining the inside of the eye is the retina, a light-sensitive layer of tissue. It is composed of various layers with the photoreceptive cells being located at the back of the retina, and for this reason it is known as an inverted retina. This feature of the eye remained something of a mystery for some time, and was likened unto "placing a thin diffusing screen directly over the film in your camera" [8]. In 2007 it was found that the Müller cells acted like optical fibres which channelled light through the retina to the photoreceptive layer at the back [9].

There are two principal types of photoreceptors: Rods and cones. In a bright environment, with a radiance higher than 10 cd/m^2, it is principally the cones that are used; this is photopic sight. The cones give the capacity for colour discrimination and high acuity vision. In a very dark environment when the radiance is less than 5×10^{-3} cd/m^2, under starlight for instance, only rods are used; this is scotopic sight. Rods do not allow colour vision, but are more light sensitive than cones. The range in between these uses both rods and cones and is known as mesopic sight.

Overall there are 20 times as many rods as there are cones [10], but they are not evenly spread across the retina. Near the centre of the retina is the macula, the important region onto which the light from our point of fixation is directed. The macula can be sub-divided into four concentric regions, as illustrated in Figure 1.2. The innermost region, the foveola, contains only cones. It covers the central 1° 20' of the visual field*, is about 350 µm in diameter, and has the highest density of cones found anywhere in the retina. The fovea extends an additional 750 µm around the foveola, making it about 1.85 mm in diameter and covering the central 5.5° of the visual field; the preponderating majority of photoreceptors in this region are cones. The remaining part of the macula is composed

* A rule of thumb for the field of view: At a distance of 30cm, 2° spans 1cm on the page.

of the parafovea, 500 μm wide, and the perifovea, 1.5 mm wide, in which rods become increasingly more numerous than cones. Beyond the macula is the periphery, which makes up the majority of the area of the retina. Here there are about 10 rods for every cone [5].

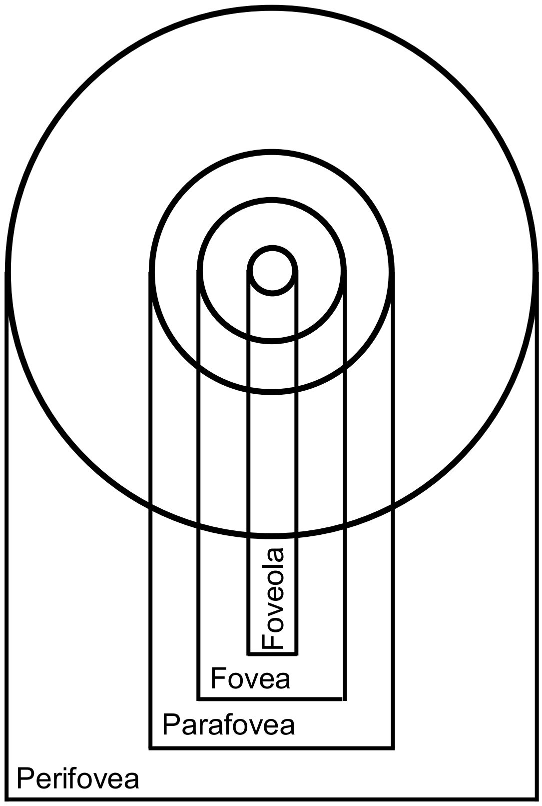

Figure 1.2. Schematic diagram of the macula, showing the four concentric regions [11].

The dominant role of the fovea in vision is illustrated by the way we continually move our gaze to centre on the precise point of interest, as opposed to using a more peripheral region to look at it. This is further underscored by considering that 40% of the primary visual cortex is used to process just the central 5° of the visual field [11]. The fovea provides the highest visual acuity, as illustrated in Figure 1.3, and so is most useful for anything that requires looking at a specific place. The periphery, however, plays an essential role in motion detection, spatial orientation and locomotion [12].

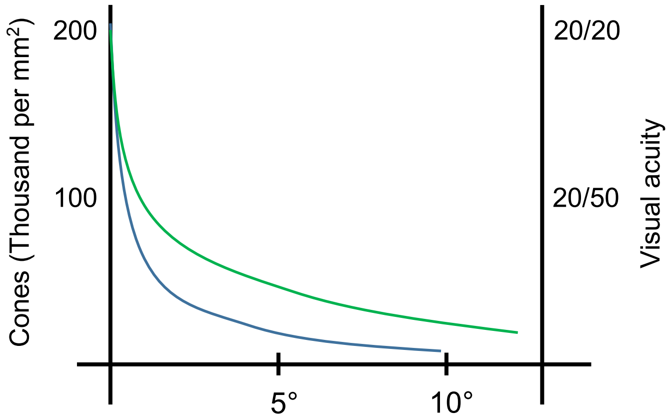

Figure 1.3. An approximate plot of the visual acuity (green curve) and cone density (blue curve) which rapidly decline with increasing eccentricity [13].

1.3.2 Performance measures of vision

The most commonly used measure of vision performance is visual acuity. The standard test is the Bailey-Lovie chart [14], Figure 1.4a, which consists of a series of black letters of progressively smaller size printed on a white background. The chart is viewed at a fixed distance and the smallest letter size that can be read determines the subject's visual acuity. This is useful for measuring the conditions of myopia and hyperopia, amongst others. It is related to many real-world tasks, and specifically those that require fine details to be resolved.

Another important measure of visual performance is contrast sensitivity. This can be subdivided into colour contrast, differences in chromaticity, and luminance contrast, differences in luminance. The latter is characterised by the Weber contrast, the ratio between the background subtracted image and the background [15]. Many real-world tasks do not take place in optimally lit conditions, and this is where one's contrast sensitivity is most useful. The standard test is the Pelli-Robson contrast sensitivity chart [16], Figure 1.4b. It consists of a series of letters printed on a white background in progressively lighter shades of grey, thus with progressively lower contrast. The lowest contrast letter that the subject can read provides a measure of their contrast sensitivity. This test has proven to be quick and reliable in a clinical setting [17].

Contrast sensitivity is not constant over all visual frequencies. It can also be measured with sinusoidal gratings where the transition from dark to light is smooth rather than abrupt, using the Ginsburg Contrast Sensitivity Chart, Figure 1.4c [18]. As well contrast being a parameter, the frequency of the sinusoid is also a parameter, thus their sensitivity is measured as a function of spatial frequency. The contrast threshold at which the gratings can be discerned is measured, and its reciprocal is defined as the sensitivity. The contrast sensitivity is plotted against spatial frequency and the result is the contrast sensitivity function. For normal vision, the contrast sensitivity function peaks at about six cycles per degree of visual angle [19].

Visual adaptation is the phenomenon whereby the perception of stimuli does not remain constant over time…

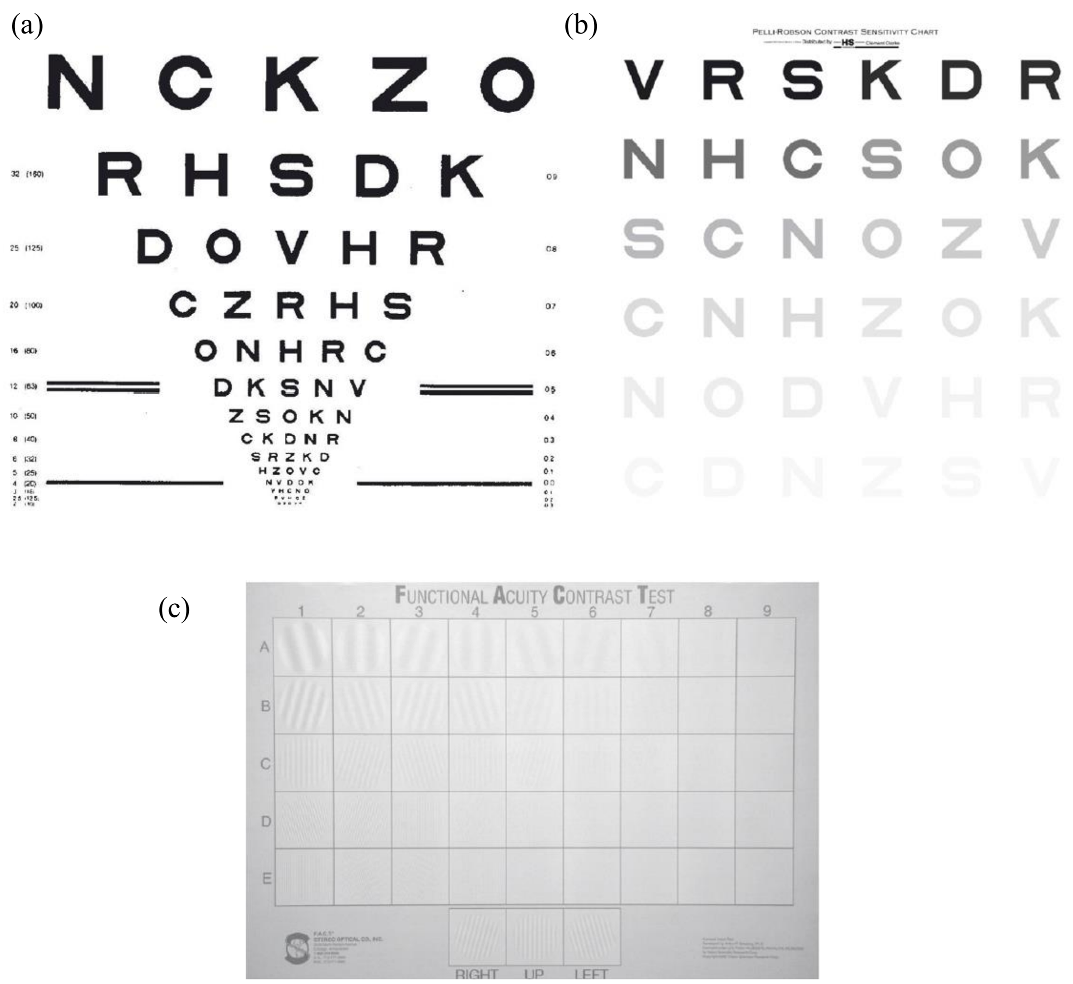

Figure 1.4. Clinical vision testing: a) Bailey-Lovie visual acuity chart, b) Pelli-Robson contrast sensitivity chart, c) Ginsburg contrast sensitivity chart. Reprinted from Drug Discovery Today: Technologies, **4**(2), B. Drum, D. Calogero, and E. Rorer, "Assessment of visual performance in the evaluation of new medical products," 55-61, Copyright (2007), with permission from Elsevier.

Valuable information about visual performance can also be obtained by testing visual acuity at low contrast. At contrast levels above about 20%, visual acuity is almost constant, but below this it is strongly dependent on contrast [19]. Therefore, either in situations with low contrast, or for conditions that affect contrast sensitivity, having a measure of low-contrast acuity is important. Low-contrast acuity can be tested using a series of letter charts, with the print of each chart being a different contrast level [20,21].

The field of view, where the area and extent of healthy vision is mapped out, is another important measure of vision. In normal vision, almost a full hemisphere of viewable area is possible with no gaps (the blind spot caused due to the optic nerve creating a break in the retina is compensated by the other eye). Some eye conditions cause blind regions in the visual field, called scotomas. Automated perimetry is the standard way to map out and measure the visual field [22]. The subject's head rests in front of a concave dome with one eye covered and a light stimulus is shown at various points. If the stimulus is seen, the subject presses a button. The field of view can thus be calculated.

1.3.3 Common causes of low vision

Low vision describes a state of significant visual impairment that cannot be corrected through simple measures such as refractive lenses or medication, or through surgery [23]. It does not describe a state of total blindness, and so indicates that there is some useable vision left. Assistive technologies, or low vision aids, seek to help the user make the most of their residual vision. Two common types of visual impairment are central and peripheral field loss.

The most common cause of low vision in the Western World is age-related macular degeneration (AMD) [24]. Its most significant symptom is a central scotoma – a region of blindness in the centre of the visual field. It is usually accompanied by a loss in contrast sensitivity [20]. A scotoma of the size usually found in AMD would barely be noticed if it occurred in any other part of the retina. However, as the macula has the highest density of photoreceptors, giving highest acuity vision, and because we are accustomed to using it for the majority of daily tasks, it will often render the patient legally blind.

There are two types of AMD: Neovascular, or wet, and atrophic, or dry. Underneath the retina is the vascular layer called the choroid which provides oxygen and nourishment to the retina. Wet AMD occurs when new blood vessels in the choroid invade the retina and leak blood which can cause scarring and damage to the macula [25]. This can rapidly cause severe damage to vision. Fortunately, however, there is a cure. Medication can be administered to prevent the growth of new blood vessels, and laser surgery can be used to destroy abnormal blood vessels.

As a person ages, the choroid beings to break down and become thinner. This means that the retina can less efficiently receive nutrients and expel waste. This can lead to a build-up of drusen – small, yellow deposits. This build-up of drusen, combined with the lack of nutrients, can cause damage to the photoreceptor cells [26]. This is the cause of dry AMD. Unlike wet AMD, this is a relatively slow process in which the patient gradually notices a deterioration in their central vision. There is, however, no cure. Patients are thus reliant on low vision rehabilitation.

The most common causes of peripheral field loss, which can be described as tunnel vision, are retinitis pigmentosa and glaucoma. Retinitis pigmentosa is a genetic condition that causes the photoreceptors in the peripheral retina to atrophy [27]. There is no known cure. Glaucoma is a term that describes a group of eye conditions that result from optic nerve damage. There are drainage channels between the iris and the cornea, called the trabecular meshwork, which drain away aqueous fluid. If these channels become blocked then the build-up of aqueous fluid can cause the eye pressure to rise and result in damage to the optic nerve [28]. Using eye drops can reduce the pressure in the eye and prevent damage. However, damage that has been caused by glaucoma cannot be repaired, thus patients seek assistance in the form of low vision rehabilitation.

1.3.4 Reading requirements for normal and low vision

For people with AMD, the task they most want their eyesight for is usually reading [29]. Reading is also widely used in the assessment of the performance of the eyes, and not only in terms of letter recognition on a letter chart; the ability to read a newspaper at a normal distance of 40 cm, using refractive correction if necessary, is a performance-based definition for low vision [30]. In the assessment of many low vision aids a measurement of the reading speed of the user is used to judge the effectiveness of the aid. Thus it is worth considering here the prerequisites of the ability to read, both for normal vision and for those with a damaged macula.

The basic requirement for reading is to have sufficient visual acuity to recognise the letters. However, recognising one letter at a time is insufficient; reading requires the simultaneous overview of a group of letters [13]. The minimum field of view (FoV) within which characters need to be seen clearly is about 2° to the left and right of the point of fixation, roughly corresponding to the fovea [13]. For fluent reading, use of the parafovea is necessary and a span of 5° to the right and 1.3 – 2° to the left is used (when the reading direction is left to right) [31]. It is also necessary to have stable fixation and control of eye movements.

With regard to the requirements of the text itself a number of factors can improve the ease and speed of reading, these include: size of the text, contrast, type of font, letter spacing, luminance and presentation [32]. In their series on the psychophysics of reading, Legge *et al.* found that, for normal vision, characters that subtend an angle in the range 0.3 – 2° allow a maximum reading rate; for characters within this range, reading rate was very tolerant to contrast reduction, though it did decrease at low contrast; contrast polarity (black on white or white on black) is found to have no effect; reading speed versus colour contrast and versus luminance contrast have the same trend; only slight differences in reading acuity and reading speed were found between Courier and Times fonts [33–36].

There are a number of differences found in this series for people with low vision as opposed to normal vision. Obviously the term low vision encompasses a wide variety of pathologies so precise statements about reading requirements cannot be made like they can for normal vision. Nevertheless, some general comments can be made if low vision caused by central field loss is assumed: magnification is usually required to achieve high enough reading acuity; the role of contrast is more important than for normal vision; luminance contrast is more important than colour contrast; white text on a black background can sometimes increase reading speed, as light scatter is reduced; the choice of font makes a bigger difference than in normal vision, with Courier allowing better reading acuity and reading speed than Times [35–38]. In general, more care needs to be taken to maximise the reading performance of people with low vision than normal vision.

1.4 Head-mounted displays in low vision aids

1.4.1 Low vision aids

Low vision aids (LVAs) are diverse in character but can be divided into two categories according to their function: Those which translate visual information into alternative sensory information, such as sound or touch (sensory substitution); and those which alter visual information to render it more visible to the user (vision enhancement). Aids in the former category would include text readers and barcode scanners for those which translate into sound, and vibrating devices and the white cane for those which translate into touch. This category would of course be the only option for those with no light perception. However, it is natural for those with low vision to want to make the most of their remaining vision. It is the LVAs in the vision enhancing category that are relevant here.

Many types of low vision aids use magnification. This has the effect of filling a greater portion of the visual field with the image, thus lessening the effect of the scotoma. The optical magnifier has been the mainstay of visual rehabilitation for many years; it is simple, easy to use and inexpensive. However, its limits in magnifying power, field of view and viewing distance have now been surpassed by electronic magnifiers [4]. These are widely available in handheld and desk-mounted formats and often include a zoom function, brightness and contrast controls and colour inversion [39]. They have proven to improve reading ability, often beyond what is possible using optical magnifiers [40–42]. But the electronification of magnifiers is only the beginning of harnessing technological advances for the visually impaired [43].

Another strategy for low vision rehabilitation, often used in conjunction with an aid, is the technique of eccentric viewing. This is useful for those with a reduced visual field, particularly if it is the central field that is impaired. For healthy vision, the preferred retinal locus (PRL) – the centre of visual activity – is the fovea. If the fovea is damaged then one or more PRL can be chosen and used as a “pseudofovea”. These PRLs can be formed without the conscious decision of the individual but form naturally over time as the demands of everyday visual tasks surpass the capacity of the damaged fovea [44]. Eccentric viewing training assists patients to fixate objects and perform daily tasks using either their PRL or a trained retinal locus (TRL) [45,46]. Often the PRL is at a position unfavourable for reading, and slows reading speeds markedly, so by using a TRL speeds can be improved [47]. Eccentric viewing needs to be done with the aid of a magnifier due to the lower acuity of the peripheral retina [13].

An aid that can be used to automatically direct light on to the PRL is a pair of prism spectacles. Prism spectacles incorporate a prism into a pair of glasses and redirect light entering the eye onto the PRL, as illustrated in Figure 1.5. The literature is inconsistent in its view of the efficacy of prism spectacles. One randomized, controlled trial, which involved 225 participants with AMD, found no significant improvement in visual acuity, reading speed or critical print size and responses to their questionnaire suggested that prism spectacles added to their problems [48]. However, another study, involving 100 AMD patients, found a significant and sizeable improvement in best-corrected visual acuity [49]. A review on the use of prisms for the vision rehabilitation of people with damaged maculae, published in 2013, included these two studies as well as seven others [50]. The review points out the variation in methodology between the studies and evaluates the strength of their evidence. It highlights that compliance (whether the participants actually used the prism glasses) is an important factor that was omitted in some. It concludes that none of the studies present evidence compelling enough to either conclusively endorse or reject the value of prism glasses.

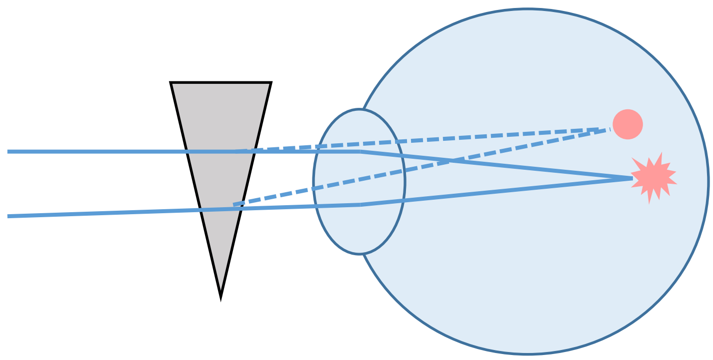

Figure 1.5. A simplified illustration of image relocation using a prism. Solid lines are rays without the prism that lead to a damaged area of the retina and dashed lines are rays with the prism [49].

1.4.2 Head-mounted displays

The head-mounted display (HMD) is a niche but growing class of electronic display system. An HMD comprises a miniature electronic display screen in close proximity to one or both eyes viewed through compact imaging optics which cause a highly magnified virtual image of the miniature screen to appear at a comfortable distance for the viewer [51,52]. A simple HMD can be made by mounting a smartphone into a frame which incorporates the necessary optics at a suitable distance. This idea was popularized by Google Cardboard and can be used as a budget “virtual reality” system. Another class of HMD features a partially transparent screen instead of the typical opaque type such that the user’s view of their surroundings is not occluded. When the display screen is housed in something resembling a spectacle frame it is referred to as “smart glasses”. This technology continues to be actively developed with many products currently available only as developer kits. But with numerous vendors set to release commercial products the technology is expected to become much more widespread; the smart glasses market is expected to almost double in the next 4 years [53].

1.4.3 A review of head-mounted displays in low vision aids

Desk-mounted and handheld displays are commonly available in LVAs. Since the start of the nineties, research and development has gone into offering a head-mounted alternative. Many also included a camera to provide a live-feed to the display. Wolffsohn and Peterson [4] introduced the term Electronic Vision Enhancement System (EVES) to describe display and camera systems for the visually impaired and to replace the more general term of closed-circuit television (CCTV).

The first EVES to use an HMD was Bright Eyes by Optolec [54], but the first one to head-mount the camera too, and which also included built-in image processing capability, was the Low Vision Enhancement System (LVES) [55]. A number of studies that tested LVES on participants with low vision [56–60] found that it did improve visual acuity and contrast sensitivity, but its imposing size and weight and reduction in field of view meant it never became a commercial product. A succession of products followed that had the same functionality but built on technological advances; these included V-Max and Jordy by Enhanced Vision, NuVision by Keeler Ltd. and SightMate by Vuzix. Three studies [61–64] tested some of these products and one [63] found an improvement in distance acuity compared to optical aids but no improvement in contrast sensitivity and a decline in reading and writing speed.

A number of similar devices were developed in a research setting, including: Wearable LVA [65–70]; Retinal Projection System [71,72]; device with transparent display for minification and magnification [73–78]; SERBA (reconfigurable electro-optical aid system for low vision) [79,80]; depth based navigation aid [81,82]; ForeSee, with five enhancement methods [83]; applying optokinetic stimulation on an HMD to improve hemispatial neglect [84]. Various models of night vision goggles were also studied for aiding night blindness [85–92].

A number of new systems have recently been proposed but have yet to be fully developed: real-time television enhancement system [93]; real-time contrast enhancement system that copes with abrupt changes in lighting [94]; user-reconfigurable edge enhancement system [95]; magnifying contact lens [96]; using Google Glass as a platform for edge enhancement [97], to magnify a smartphone screen [98], and for expanding the visual field [99]; brightness and contrast enhancement using Epson Moverio BT-200 [100]. oxSight (oxsight.co), GiveVision (give-vision.com), DigiGlasses (digiglasses.eu) and eSight (esighteyewear.com) are developing low vision aids based on smart glasses.

Table 1.2 compiles key information from studies investigating the benefit of LVAs which incorporate HMDs. Data compiled are: Sample size and type; the LVA used as an intervention; the measure used to assess benefit; the main results.

Table 1.2. Table of studies into the benefit of LVAs that use HMDs.

Ref. Year	***Participants***	***Intervention***	***Measure***	***Results***
[63] 2004	20: 10 with AMD, 10 with EOMD	Jordy, Flipperport, Maxport, NuVision	Visual function, reading ability, write a cheque, identify groceries	Distance and intermediate acuity using Jordy and Flipperport were significantly better than optical LVA but worse and no different using NuVision. No significant difference in contrast sensitivity across aids. Reading speed was slower than optical LVA for all 4 devices, except for EOMD using Flipperport on small print size. No significant difference in identification time across aids. Cheque writing was faster with the optical LVA.
[64] 2009	20: 10 with AMD, 10 with EOMD	Jordy, Flipperport, Maxport, NuVision	Subjective evaluation	No one device was given strong preference across aspects of evaluation. Newly diagnosed patients responded most positively, but no other trends were found in age, gender, diagnosis or previous CCTV experience.
[71] 2004	21 with central scotoma	Retinal projection system	Smallest text size with max. reading speed	In 14 subjects, the critical text size was smaller than while using an HMD. 17 read an equal or greater number of characters of the smallest size compared to the HMD.
[70] 2004	4 legally blind	Wearable LVA	Icon recognition, mobility	2 unable to use device due, possibly due to sensitivity to red light. Subject 1 identified 89% of icons and subject 2 97%. Only hazards above waist height could be spotted and manoeuvred around.
[92] 2006	11 with night blindness	MultiVision night vision goggles	Questionnaire after 1 and 2 years of use	By 2nd year 2 participants had stopped using device and 7 used it at least twice a week. Fewer problems with mobility in dark after 1 and 2 years. After 2 years, increase in sense of independence.

[76] 2009	7 with tunnel vision, 12 controls	Transparent HMD mini/ magnification	Collision envelope and judgement uncertainty	For patients, neither collision envelope or uncertainty were affected by minification – thus collision risk was not overestimated. For controls, collision envelope for intended walking increased by 30% but otherwise measures remained unchanged.
[77] [78] 2011	3 with VA worse than 6/60	Transparent HMD mini/ magnification	Visual function, mobile search	VA improved to 6/6, 6/10.5, 6/14.4. CS improved by 30%, 92% and 191%. When searching for targets in a large room, they had to approach every target before confirming the correct one, but with the device could identify most targets from the start point.
[79] 2009	8 with RP, 6 with LV, 9 controls	SERBA	Visual function	The minified contours expanded the visual field by 3 to 4 times in 7 out of 8 RP subjects without significantly degrading residual vision. For those with LV and the controls, VA increased in proportion to magnification.
[80] 2011	6 with RP	SERBA	Mobility, perceived mobility	The number of contacts with obstacles decreased whilst using SERBA, but so did the walking speed. Subjects rated themselves more confident at locating and avoiding obstacles with the SERBA, but at determining obstacle distance without it.
[81] 2013	18 (11 have useful residual vision)	Depth-based navigation aid	Search task within HMD	3 with advanced RP were successful with targets up to 30° from the centre and took 10 to 20 seconds to locate the target at 30°; the rest could see targets up to maximum of 60° took between 1 and 9 seconds at 30°
[82] 2015	11 with LV, 5 controls	Depth-based navigation aid	Mobility task	Mobility performance improved those with poorest eyesight, but walking speed was slower and hesitations increased.

[83] 2015	19 with LV	ForeSee	Perceived reading ability	Preference was most often indicated for magnification and for text extraction for distance reading and a combination of methods.
[84] 2015	14 with hemispatial neglect	HMD with optokinetic stimulation	Line bisections	Performance improved using the device.
[98] 2016	4 with LV and 8 controls	Google Glass magnification	Calculator and app tasks	The time required for the calculator task was shorter using the device, and was the same for the app task.

HMD – head-mounted display; LV – low vision; LVA – low vision aid; RP - retinitis pigmentosa; VA – visual acuity; CS – contrast sensitivity; AMD – age-related macular degeneration; EOMD – early onset macular disease; SERBA - Sistema Electro-óptico Reconfigurable de Ayuda para Baja Visión [reconfigurable electro-optical aid system for low vision].

1.5 Conclusion

The background to the problem tackled by this thesis, reading with a diseased macula, was described. First, a brief description of the human eye, with particular reference to the areas and characteristics of the macula, was given. The principle methods for measuring various aspects of eyesight, and the common causes for incurable deterioration in eyesight, were explained. Finally, the requirements to be able to read were outlined, both in terms of visual function and the characteristics of the text being read.

A review of the use of head-mounted displays in low vision aids was then made. This began with an overview of the various types of low vision aids, and a description of head-mounted displays. A thorough literature review was then reported, including findings from both the commercial and academic sectors. In particular, the details of the participant trials of these devices was compiled. Despite many of these studies showing benefit to the visually impaired, no head-mounted LVA is currently widely available. More work is needed to investigate more modern devices, characterizing their suitability for the low vision population, and developing techniques for their use in enhancing visual function.

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CHAPTER 2

Review of image processing for the visually impaired

The contents of this chapter have been updated, expanded and adapted from the paper entitled, 'High Tech Aids Low Vision: A Review of Image Processing for the Visually Impaired' [1], *of which I was the lead author, published in the peer-reviewed journal Translational Vision Science & Technology. Republished with permission of the Association for Research in Vision and Ophthalmology; permission conveyed through Copyright Clearance Center, Inc..*

2.1 Introduction

Modern image processing techniques allow for a variety of novel and more advanced tools to aid the visually impaired. This generally implies applying mathematical algorithms onto an electronic image which then outputs a version of that image with certain of its parameters modified, such as its spatial frequency content, brightness range or the boldness of its edges. Visual impairments present their own set of challenges to be addressed by image processing. In this context we aim to focus our review, synthesizing and sifting published data, for evidence of how novel image processing tools might usefully enhance sight quality of life for patients with sight-affecting disease.

2.2 Methods

A Web of Science and PubMed search was conducted to identify papers relevant to image processing for the visually impaired. Keywords such as low vision, visually impaired and visual rehabilitation were used in conjunction with keywords such as image processing and contrast enhancement. The web of references and citations (found in Web of Science) was traced to track down papers not picked up in the database searches. Only studies done to investigate these technologies for the visually impaired were included, thus more general studies done about the technology itself were not included.

2.3 Results

The literature search yielded 37 papers which investigated the benefits of image processing techniques on the visually impaired. 11 studies were on text, 18 on images and 11 on video (3 papers tested 2 media). Table 2.1 collates the core data from each of these studies: The year of publication; the number and visual condition of the participants; whether text, images or video was processed; the type of image processing used; the outcome measure; and the main results. The research is then categorized according to the image processing technique investigated, highlighting important results for each.

The specific aims of each approach differ and accordingly have different outcome measures. For example, when the techniques are applied to text they not only seek to increase visibility but to reduce the strength of magnification needed, both of which increase reading speed [2,3]. Examples of the range of these techniques are shown in Figure 2.1. Non-text images have a wider range of distinct techniques applied as a result of their added complexity and some examples are shown in Figure 2.2. We discuss this range of potential strategies used to enhance the visual experience stratifying according to the principles of image processing that they involve, beginning with contrast and spatial frequency manipulation and progressing to more advanced and recent techniques.

Table 2.1. Table of experimental studies about image processing for the visually impaired, ordered by type then reverse chronological order.

Ref. Year	***Participants***	***Type***	***Intervention***	***Measure***	***Result (enhanced vs unenhanced)****
[43] **2014**	3 with simulated low vision	Text	Edge enhancement overlay on transparent display	Contrast sensitivity	Participants with normal vision and a diffuse filter had a log contrast sensitivity of 0.75 without the enhancement and 1.5 with the enhancement (the limit of the camera's sensitivity).
[54] **2014**	35 with simulated central scotoma	Text	Mixed linear and non-linear magnification	Reading speed	Median reading rate was 1.4x (range of 1x to 2.4x) faster with mixed magnification than liner magnification for 2.5° scotoma and 1.2x for 0.5° and 1.5°.
[55] **2012**	21 with AMD of which 20 had CFL, 9 controls	Text & Image	Jitter	Word recognition speed; identification of facial emotion	Word recognition speed increased by average of 66±9.4% (101% for severe visual impairments). Emotion identification increased by 100 to 180%.
[52] **2005**	18 with simulated central scotomas	Text	Remapping	Reading rate	For scotomas 8° and larger the reading speed improved by between 27% and 54.1%.
[28] **1998**	7 with AMD, of which 5 had CFL	Text	Individualized compensation filter, based on CSF	Reading rate	Reading rate increased by 240% on average, with a range between 170% and 450%.
[29] **1995**	10 with simulated central scotomas of 4°, 8°	Text	Remapping	Reading rate	Reading rate increased for all participants, ranging from slight to doubling. Average improvement of 5wpm from 63wpm for 4° scotoma; 10wpm from 35wpm for 8°.

[51] 1995	2 with CFL	Text	Remapping	Reading rate	Reading rate increased by 4.4wpm from 109.8wpm in participant A and by 5.1wpm from 30.8wpm in B.
[17] 1995	31 with LV of which 28 had CFL	Text	Adaptive enhancement algorithm	Reading rate	14±6% average increase in reading rate, with a range of 100% decrement to 125% improvement. 66% of patients improve reading rate.
[16] 1994	32 most with CFL	Text	Adaptive enhancement algorithm	Reading rate	20 increased rate, but average increase of 10.4% not statistically significant. Near threshold group increased by 25.4% but large variance prevented significance.
[26,27]1989	3 with CFL; 2 controls	Text	Individualized compensation filter, based on CSF	Performance at recognizing 5-letter words; reading rate	The necessary magnification decreased by 32%, 48% and 57% for the 3 visually impaired observers with an associated reading speed increase of 50%, 150% and 250%.
[25] 1988	3 with ARM, 1 age-matched control	Text	Individualized compensation filter, based on CSF	Performance at recognizing 5-letter words (as a function of magnification)	The necessary magnification decreased by 27%, 42% and 70% for the 3 ARM observers, and this trend was positively correlated with severity of vision loss.
[35] 2012	24 with CFL	Image	Contour enhancement	Time and accuracy locating object within image; perceived visibility	On average, no improvement in search time, though there was for a sub-group of 6; significant preference for enhanced images.
[36] 2012	17 with AMD	Image	7 techniques incl. wideband, object classification, contrast	Time and accuracy locating object within image; preference rank	On average, no significant difference in time and accuracy for any method; least modified images preferred.

[8] 2012	19 with LV	Image	Contrast enhancement	Time and accuracy locating object within image	On average, no significant difference in time and accuracy, though a certain acuity range improved.
[37] 2012	55 with simulated central scotoma	Image	Contour enhancement	Time and accuracy locating object within image; perceived visibility	Search time decreased by 13% for older adults and non-significant difference for younger adults; both groups preferred enhanced images.
[11] 2011	1 with CFL, 6 controls	Image	Histogram-based enhancement	Perceived quality	Enhanced images preferred by all.
[33] 2010	27 with LV	Image & video	Edge enhancement and cartoonization	Perceived visibility	15 preferred the enhanced images; 20 preferred enhanced video.
[32] 2011	14 with AMD, 33 controls	Image	Background attenuation	Object recognition performance	Performance improved for enhanced images for those with AMD and for controls.
[53] 2010	20 with simulated tunnel vision, controls	Image & video	Scene retargeting	Time to count objects or events.	Significant reduction in time of 50% for 11° FOV and 35% for 22° FOV was achieved for images, with a slight improvement for controls. % of events detected in video improved by 136%.
[6] 2009	9 with maculopathy	Image	Preferred 2 filters out 9 choices	Recognition of 4 facial expressions	Performance significantly improved viewing enhanced images compared to original.
[31] 2008	3 with AMD	Image	Edge enhancement and scene simplification	Object recognition performance	Improved performance with enhanced images over original images.

[50] 2005	15 with AMD, 30 controls	Image	Darkening image background	Object recognition performance	Performance improved with enhanced images for all participants.
[4] 2005	28 with LV of which 19 had CFL	Image	Various generic filters, adaptive enhancement, adaptive thresholding	Perceived visibility compared to original, scored from -100 to +100	Significant preference of some filters over original, scoring an average of just under +20 for some image types; significant preference to original over degraded.
[7] 2004	27 with retinal diseases of which 15 had CFL	Image	JPEG-based enhancement	Perceived quality compared to original, from 5 levels	7 preferred images with individually selected enhancement, all preferred the original image to the degraded one.
[34] 2004	23 with LV of which 17 had CFL	Image	Wideband enhancement	Perceived quality compared to original, from 5 levels	89% preferred the enhanced image over the original image; the perceived improvement was significant for 22% of participants.
[19] 1999	16 with low vision	Image	Adaptive enhancement, scene classification	Identifying objects	Scene classification technique increased performance from 40% to 87.5%; adaptive enhancement reduced performance to 26%.
[14] 1994	11, most with CFL	Image	Self-selected filter	Determine if image is a celebrity or not; individually tuned enhancement	Task too easy for 6, thus no improvement; 3 had a non-statistically significant improvement; 2 no improvement.+ Enhanced images were preferred.
[18] 1991	46 with LV of which 38 had CFL	Image	Adaptive filtering and adaptive thresholding algorithms	Determine if image is a celebrity or not	Ability to recognize celebrities improved in 39 of the 46 participants, with the improvement being significant ($P<0.05$) in 19 of them.

[24] 2008	24 with CFL; 12 controls	Video	Adaptive enhancement	Preference comparison	88% of visually impaired viewers preferred enhanced video over the original; controls preferred only low enhancement level or original.
[38] 2007	102 with LV of which 57 had AMD, 10 controls	Video	Edge detection (Prewitt, Sobel)	Perceived quality, scale 0-10	Enhanced videos were on average preferred by LV viewers with no correlation between type or impairment and preference; controls preferred original.
[10] 2007	24 with LV, 6 controls	Video	Contrast enhancement	Self-adjusted enhancement	All participants chose to enhance the videos significantly above zero with the average enhancement significantly more for LV subjects.
[23] 2007	20 with LV of which 16 had CFL	Video	Adaptive enhancement algorithm	Perceived quality comparison	Enhanced videos were preferred 72% of the time compared to 43% for non-enhanced videos.
[22] 2005	56 with CFL	Video	Adaptive enhancement	Recognition of visual details and perceived quality of 7 measures scored 0 – 50	Enhancement did not improve performance, perhaps due to a ceiling effect. Perceived image quality significantly increased for enhanced video.
[9] 2004	24 with CFL	Video	MPEG-based contrast enhancement	Preference comparison, 3 levels of preference	Left/right side bias found in 11, a preference was for enhancement in the remaining 13.
[21] 1999	20 with CFL	Video	Adaptive enhancement algorithm	Perceived quality	Statistically significant preference.

[20] 1996	19 with CFL	Video	Adaptive enhancement algorithm	Recognition of visual details and perceived quality	14 improved performance; statistically significant improvement to 76±10% correct from 71±12% (compare to 15% difference to normal viewers for unenhanced). Preferred by 4.
[16] 1994	21 with CFL	Video	Adaptive enhancement algorithm	Recognition of visual details and perceived quality.	Excluding 4 who saw all details without enhancement, performance improved for all with average increasing from 57% to 74%. All but 1 preferred the enhanced video.

LV – low vision; CFL – central field loss; AMD – age-related macular degeneration; FOV – field of view; CSF – contrast sensitivity function

* Where variations over the technique were tested, results for the most successful variation are given.

2.3.1 Contrast enhancement

A relatively simple starting point to improve an image is to enhance its contrast. As little subjective input is needed, any of the standard techniques for contrast enhancement can be easily implemented, often in conjunction with other enhancements. These generic techniques (Figure 2.2d) are investigated in studies by Leat *et al.* using CRT screens [4–6] which found significant preference given to enhanced images over the original as well as improved performance at recognizing facial expressions. Another group using enhanced contrast on images [7,8] and video [9,10] found a preference over the original but no significant improvement in locating objects within the images. Two groups have recently developed contrast enhancement methods especially for use on head-mounted displays, but studies need to be conducted to test them [11–13].

2.3.2 Spatial frequencies

Using information from spatial frequency content, contrast enhancements can be targeted to the most important image features for the visually impaired, first investigated by Peli *et al.* [14]. For example, by boosting the high spatial frequency content the image can be sharpened or have its edges enhanced. The generic techniques that do this were evaluated alongside custom-devised algorithms in the studies mentioned above by Leat *et al.*. The first such custom-devised method for the visually impaired, called adaptive enhancement, [15] increases the contrast of high frequencies and, to allow a greater dynamic range reduces the contrast of low frequencies. This has been widely tested on the visually impaired, with studies applying it on text [16,17], images [14,18,19] and video [16,20–24]. It was found to improve face recognition in static images, increase recognition of visual details in video and was generally preferred over the original. However, an independent study [19] found that it reduced performance at identifying objects.

Lawton used the contrast sensitivity function of the patient to tailor the contrast enhancement to the most important frequencies for that individual (Figure 2.1a). The trials that tested this method for text on a CRT monitor [25–28] showed dramatic improvement in reading speed, between 1.5 and 4.5 times what was achieved reading the unenhanced text. However, was not be replicated by Fine and Peli [17] who sought to make their text, displayed on a CRT monitor, as close in appearance to Lawton's as possible; they found a range of 100% decrement to 125% improvement. Leat *et al.*

highlight the differences in the two groups' techniques and the fact that Lawton *et al.* optimize the algorithm to the individual as two possible causes for the difference [4]. The reason could also be down to the varying eye conditions of participants and the low numbers in the experiments of Lawton *et al.* which weakens the strength of the evidence.

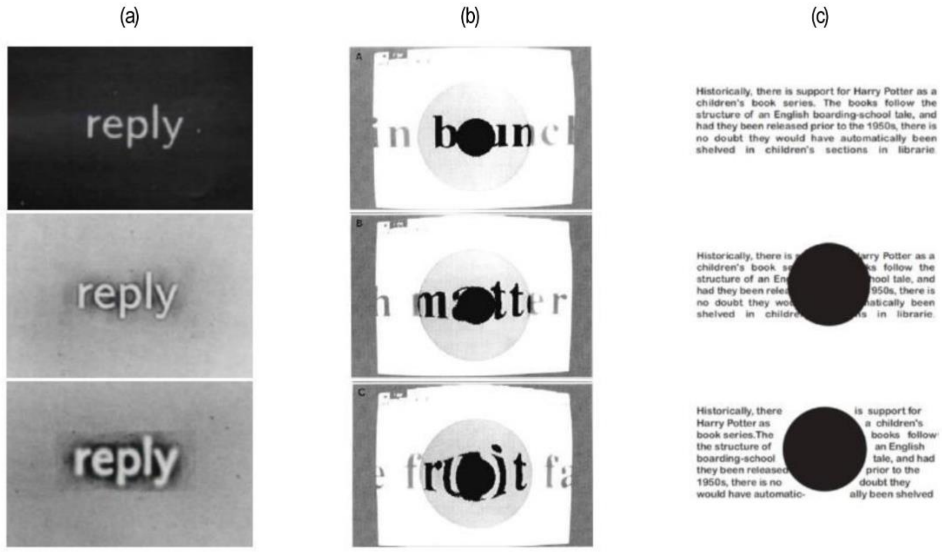

Figure 2.1. Three of the techniques for enhancement of text. a) The original image followed by two with high spatial frequencies boosted according to on the individual's contrast sensitivity function [27]; b) an unmodified image with a representation of a scotoma then two with the text remapped through warping 40% and 80% around the scotoma [29]; c) an illustration of remapping through the relocation of words around a scotoma [30]. Permission for reproduction of all images obtained from authors and publishers Wiley, Wolters Kluwer and IEEE respectively.

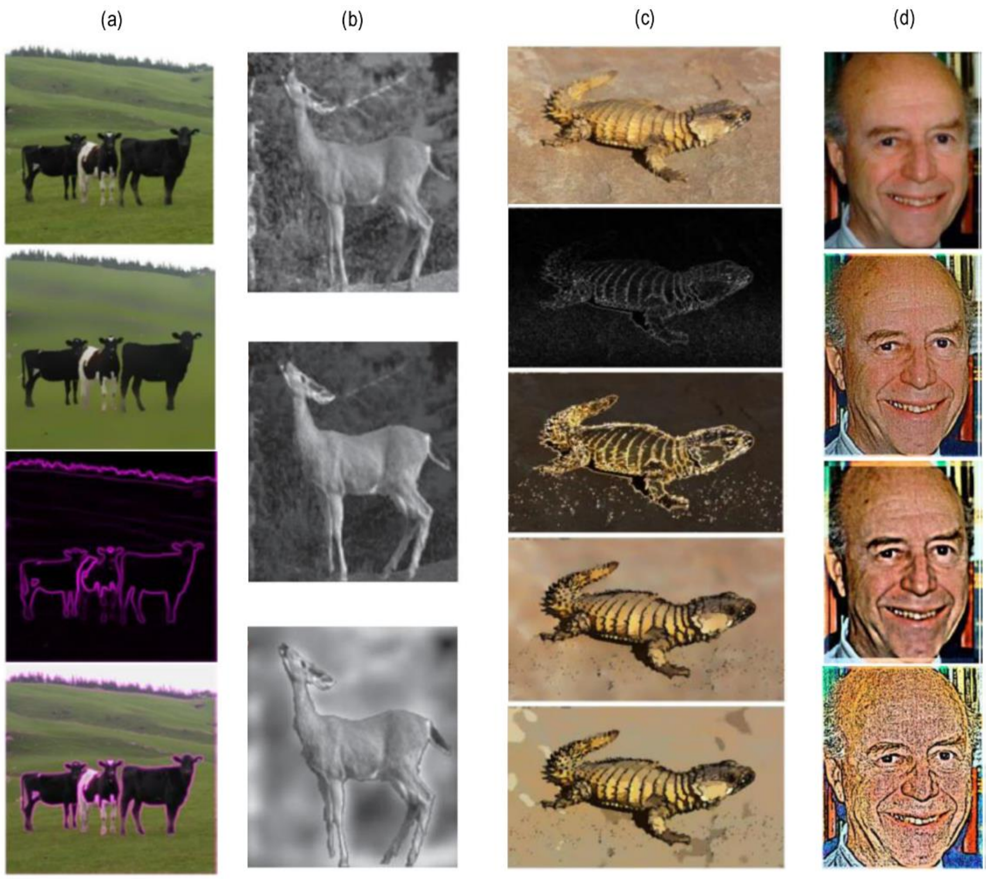

Figure 2.2. Four of the image enhancement techniques. Each column begins with the original image and is followed by these modifications: a) scene simplification, edge detection and edge enhancement of original image [31] b) darkening then attenuation of background [32]; c) gradient image, Tinted Reduced Outlined Nature, cartoon image without then with colour quantisation [33]; d) adaptive enhancement algorithm with 3 different settings [4]. Permission for reproduction of all images obtained from authors and publishers IEEE, Wiley, BioMed Central, Elsevier respectively.

2.3.3 Edge and contour enhancement

Wideband enhancement is another custom-devised approach. It is used to detect the edges within the image and then enhance their contrast by superimposing onto them dual-polarity pairs of bright and dark lines. Two studies, one using a CRT monitor [34] and the other using an LCD HDTV [35], found preference for the wideband enhanced images over the originals and, although overall there was no improvement in visual search performance, there was improvement for a sub-group of 6. However, another study [36], using an LED display, found no overall preference for it and that it offered no improvement for object location.

A different technique, which boosts the contrast of shape-defining edges whilst maintaining sharpness, was found by one study [37] using a CRT monitor to be preferred and to improve visual search time for older adults but not for younger adults. A third technique (Figure 2.2a), which enhances only the dominant edges, underwent a pilot study [31] and found it improved recognizability of image details. A major study [38] which included 102 visually impaired participants tested two generic edge detection algorithms for video on a TFT monitor. It found that, although the controls preferred the original images, those with low vision on average preferred the enhanced images, independent of impairment type, and 70% were prepared to buy a set-top box to achieve the enhancement on their television.

These techniques can be used in a particular way with a transparent display that is worn close to the eye, such as Google Glass. Peli [39] suggested using it in an augmented reality system which inputs a wide visual field via a camera, processes it in real-time to leave only the edges of the main objects so as not to obscure the natural view, then displays the edges on the transparent display [40]. The edges can either be superimposed on the natural view or, for those with peripheral field loss, they can be minified and presented to the central field. Studies done on prototypes by two groups have investigated visual function [41–43], visual search [44,45] and navigation ability [42,46,47] and found the device improves contrast sensitivity, increases visual field and shortens search time. It has been suggested that this has the potential for inattentional blindness, but when tested was not found to be a problem [48]. Recent work has also been done on a user-reconfigurable edge enhancement technique [49] but it has yet to be tested on low vision patients.

2.3.4 Background attenuation and scene simplification

Segmentation is a technique which partitions an image into multiple parts, for example to separate objects from their background. The first study [19] using this technique for the benefit of the visually impaired color-coded object types such as buildings, road and vegetation. Performance at identifying objects was significantly better than when viewing the original images and images modified with adaptive contrast enhancement. However, another study [36], which segmented the image and also darkened the background, did not find a significant difference in ability to locate objects. Two further studies [32,50], which used this technique to attenuate the background compared to the main image object (Figure 2.2b), measured performance at recognizing the object and found it to improve.

These techniques were developed for the visually impaired on the understanding that a reduction in crowding would ease object recognition. This understanding has also lead to the development of algorithms which simplify an image scene. One paper [33] investigated methods which have this effect, such as cartoonization (Figure 2.2c), but found the modified images and video were preferred by just over half the participants.

2.3.5 Remapping and retargeting

An intensive approach to overcoming blind spots is that of using eye tracking to remap text falling on the scotoma to another location on the screen. This can either be done by warping the text around the scotoma or by moving it, as illustrated in Figure 2.1b and Figure 2.1c. The majority of participants trialing this technique were normally sighted with simulated central scotomas, but two had CFL [29,30,51,52]. A modest improvement in reading rate was found in both groups. This may encourage others to update this work with the advances in technology made since its publication, perhaps allowing time for perceptual adaptation.

Retargeting, as proposed by Al-Atabany *et al.* [53], is useful for those with peripheral field loss. It involves shrinking the scene according to an importance map, such that the size of key features is maintained whilst less important features are shrunk. 20 people with simulated tunnel vision were assessed at counting objects and events on a projection wall. Using the modification, search time reduced by an average of 50% for images and percentage of events detected in video improved by 136%.

A magnification technique which preserves global information by mixing linear and non-linear magnification was proposed by Martin-Gonzalez *et al.* [54]. It was implemented using two colour cameras mounted on a binocular, see-through HMD with a 60° field of view. The reading speed of 35 participants with simulated central scotoma was measured. The mixed magnification approach increased reading over the linear magnification approach by 1.2x for 0.5° and 1.5° scotoma and by 1.4x for 2.5° scotoma.

2.3.6 Jitter

The jittering of an image would normally be considered to be degrading to quality. However, one study [55] investigated whether this effect could be used on patients with macular degeneration to improve word recognition speed and identification of facial emotion. The image, either text or a face, was made to jitter rapidly between the CRT screen's center and 0.5° or 1° of visual angle towards one of the four corners. Word recognition speed increased by an average of 66±9%, and 101% for those with severe impairments, and emotion identification increased by 100% to 180%.

2.4 Discussion

2.4.1 Image distortion levels

One difference between image enhancement for normal vision and for low vision is that there are techniques that would normally be considered a degradation of the image for normal vision but may in fact be an enhancement for low vision. For example, removing the majority of the image detail may not be desirable for those with healthy vision but for those with low vision the reduction in crowding that this brings helps to improve recognition of the main object. In general, the level of distortion chosen needs to be traded-off with the amount of visual information available. This is especially true for remapping against field loss, where significant visual information can be placed in the functioning field but at a high cost of distortion.

This is where the question of perceptual adaptation comes to the fore. For changes in sharpness, adaptation can happen within two minutes which means the enhancement due to sharpness loses its subjective effect very quickly [56]. However, more extreme techniques, such as remapping, could use the brain's plasticity to its advantage. It is worth mentioning Stratton's famous experiment of 1896, in which he used mirrors to invert the orientation of his vision and found that after several days of constant use he had adapted such that the world no longer appeared upside down [57,58]. Though more recent research is less conclusive about the extent of adaptation [59], it is nonetheless possible that an extended period of adaptation to an extreme technique like remapping may allow the brain to better interpret what is presented to it. This has yet to be investigated.

Several studies included image enhancements that could be adjusted by the patients. Given the wide spectrum of visual disabilities, this would seem an important feature to include; it allows the distortion levels to be set by each individual user and is easily achieved on an electronic display.

2.4.2 Design of experiments

All the experiment designs considered in this review measure change as a result of the intervention of image processing, and cannot be considered randomized trials. Instead, viewers act as their own controls through a comparison between the enhanced and original images; some studies additionally included degraded images as a second control.

Observer bias might arise through researchers evaluating their own technologies and many of the trials were conducted with very few participants. The high diversity of low vision disorders necessitates larger and more focused studies. Three studies sought to overcome the problem of stratifying and examining particular defects by using simulated field defects. This not only widens the pool of participants, but allows control over the defect's characteristics. However, simulations are visual instead of neurological, thus do not take into account the fact that people learn to adapt to visual deficiencies over time. Simulated defects may thus be more useful for initial testing but real ones would ultimately be required for full validation.

2.4.3 Methods of evaluation

Further challenges in the field of image processing for the visually impaired lie in developing appropriate outcome measures for evaluation of the various techniques. In terms of text enhancement algorithms, for example, visibility of text should evidently be assessed. However, this assessment is challenging as many studies have shown reading ability to be an inherently unreliable outcome measure in disease states [60]. Reading speed is the most frequently used performance measure but this can itself be assessed in a variety of ways with varying degrees of validity and reliability. In the reviewed studies reading was assessed by, for example, scrolling text at progressively faster speeds until the participant cannot read it (cf. reference [28]) or timing the reading of a text (cf. reference [52]).

The methods for measuring the success of processing techniques on non-text images are more diverse [61]. They reflect a desire to assess 'real world' visual performance rather than psychophysical constructs such as contrast sensitivity and acuity. Relatively objective performance measures were taken in 16 out of the 28 studies involving non-text images or video. These measures, and the number of studies which used them, are: identification of emotion or facial expression, 2; determining whether a given face is that of a celebrity or not, 2; recognition of visual details, such as a person's clothing or objects, 7; time and accuracy of locating a given object within an image, 5. More subjective preference measures were taken in 19 out of the 28 studies. This was done either through an interview or more quantifiable measures such as rating enhanced images as compared to the original and allowing the viewer to adjust the enhancement to their liking. The majority of participants in all but one of the studies preferred enhanced images (of at least one type) over the original.

The relationships between performance and preference measures in image enhancement are not known [35]. For instance, how does one convert between reading rate and user satisfaction? In other words, what increase in reading rate would prompt someone to use the aid? Satgunam *et al.* [35] correlated visual search performance and image preference and found no significant correlation. This may be due to the small sample size used but nevertheless highlights the challenge of finding clinically relevant objective outcome measures. Kwon *et al.* [37] correlated visual search time and preference and found a moderately high correlation for some types of images and a rather low correlation for others. In general, the current studies assess the feasibility of the techniques but tests for their validity in practice have yet to be comprehensively demonstrated.

2.5 Conclusion

The report was made of a literature review into the image processing techniques that have been applied for the benefit of the partially sighted. A compilation of findings is made that includes the outcome measures and the principal results of participant trials, and these measures and results are discussed. The studies are categorized according to the image processing technique used, and their results compared.

This field is evolving rapidly but further evidence for clinical validity of these techniques is required. In order to achieve this more robust studies are required, carried out on larger and more well-defined patient groups. Outcome measures are gradually evolving and this is an active area of research. Evaluation of the effectiveness of image processing should be ultimately held to the same standards as other clinical research in low vision. Image processing algorithms need to be tailored to specific disease entities and be available on a variety of displays including tablets and perhaps most promisingly, head-mounted displays. This field has potential to deliver real clinical benefits to a large number of patients within a short period of time. The greatest potential for progress lies in a multidisciplinary perspective, ranging from image processing and microelectronic engineering to optics and clinical ophthalmology, in order to discern and define those opportunities most likely to translate to patient care.

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CHAPTER 3

Evaluation of Head-Mounted Displays for Macular Degeneration

The contents of this chapter are an expanded report of a peer-reviewed paper of which I am the lead author [1]. Smart Innovation, Systems and Technologies, "Evaluation of head-mounted displays for macular degeneration: A pilot study", Volume 60, 2016, pp 71-81, H. Moshtael, L. Fu, I. Underwood, B. Dhillon. Content used with permission of Springer.

3.1 Introduction

The review of the use of head-mounted displays and image processing for low vision users suggested the benefit of incorporating patient input into the research and development phase of low vision aids. Thus we took the decision to conduct a pilot study early in the development process in order to gain objective and subjective data on benefits and deficiencies for low vision users inherent in head-mounted displays. This would then inform the next phase of development: to develop a reading aid based on a head-mounted display.

The most fundamental question to evaluate before head-mounted displays could be considered a suitable platform for a reading aid was the extent to which those with low vision could see, and read from, these displays. Many tests to measure visual performance exist, as described in section 1.1.3. However, it is unknown how the results of these tests correlate to the specific task of seeing and reading from a display. By way of example, there would surely be a correlation between the results of a perimetry test to measure the visual field and the amount of the display visible to the individual. But the strength of this correlation and precisely how scotomas would map to areas of invisibility on the screen would need to be determined.

What was needed was a direct measure of the extent of visibility of the screen for the user. We are not aware of tests available to take such measurements. Vision tests aim to be independent of the testing medium (chart, monitor, etc.) and to strictly control external conditions in order to yield an absolute measurement of vision (acuity, contrast sensitivity, etc.). The screen visibility tests that we propose to create, though based on vision tests, differ in that they do not aim to measure the performance of the vision itself, but the performance of the vision in seeing, or reading from, a particular display.

These screen visibility tests are used to generate objective data to evaluate the benefits and deficits of certain displays for the partially sighted users. The subjective views of such users are also valid and important measures that should be taken into account. These views are captured through use of a questionnaire and interview. This provides an opportunity for subjects to give some feedback and contribute to the direction of the research.

This chapter first presents the method of the pilot patient study and the two head-mounted displays chosen for evaluation. Subsequent sections describe three screen visibility tests, each based on a standard vision test, and the creation of a questionnaire. The results of the pilot trial are presented alongside these descriptions. An overall discussion of these results and future directions of research are finally presented.

3.2 Design of experiment

3.2.1 Participants

Ten individuals with AMD were recruited, some from the low vision clinic of the Princess Alexandra Eye Pavilion, Edinburgh, UK, and others from the Macular Society. Relevant details are included in Table 3.1. The age range was from 52 to 91 years with equal numbers of both sexes. All patients were English speaking. Informed, written consent was obtained from all participants prior to their involvement.

Table 3.1. Clinical characteristics and past experience with LVAs

ID	Sex	Age	Years since diagnosis	Sight registration status	Wet/ dry AMD	Reading acuity (logRAD score[a])	Previous use of optical LVAs?	Previous use of electronic LVAs?
101	M	59	15	Blind	Dry	1.3	Y	Y
102	F	89	5	Unregistered	Dry	0.435	Y	N
103	M	52	5	Unregistered		0.73	Y	N
104	M	78	20	Unregistered	Dry	0.8	Y	N
105	F	80	14	Unregistered	Both	0.5	Y	N
106	M	74	20	Blind	Wet	1.56	Y	Y
107	F	80	11	Blind	Wet	1.67	Y	Y
108	M	76	8	Unregistered	Dry	0.725	Y	N
109	F	74	13	Blind	Both	>1.7	Y	Y
110	F	91	25	Unregistered	Wet	0.525	Y	N

[a]logRAD is the reading equivalent of logMAR; see section 3.6

3.2.2 Ethical approval

The planned study received a favourable opinion from the Leicester South NHS Research Ethics Committee and gained formal R&D approval from NHS Lothian. The application form detailed the scientific justification, the primary and secondary research questions, the design and methodology. It required an assessment of ethical, legal and management issues. A recruitment plan was submitted, outlining the inclusion and exclusion criteria, sample size and length of participation. The consenting procedure was outlined, as were the measures to ensure confidentiality. Heriot-Watt University was the sponsor, also covering insurance and indemnity.

Several supporting documents were also submitted: The protocol, with chapters on the background, aims, research questions, a detailed outline of the methods and procedure, risk management strategy, project team and task allocation and finance; the participant information sheet; consent form; questionnaire; letter from funder; evidence of sponsor insurance; summary curricula vitae of student and supervisors; MHRA letter of no objection.

3.2.3 Apparatus

The Radner Reading Chart was used to measure reading acuity and maximum reading speed. The two head-mounted displays used, smart glasses and a smartphone headset, are described in section 3.3. A Samsung laptop was used to run the programme. Splashtop Streamer was used to screen-share via wifi between the laptop and the head-mounted displays. The Python programming language was used to develop the software, in particular making use Kivy, a GUI library. The core of the programme is the algorithm which advances the test according to the responses of the user. This means the test can be done without the aid of a clinician. In the context of the patient trial, however, the participants responded verbally and these answers were input into the programme by the person running the trial. This was to maximise ease of participation.

3.2.4 Procedure

The procedure for each participant, after consent had been given, was as follows:

1. Reading acuity and maximum reading speed were measured using the Radner Reading Chart. Participants held the chart at a comfortable angle, but at a distance of 25cm. Those who could not read the top line from this distance were allowed to hold it at a comfortable distance, with the distance measured and taken into account for the measurement of reading acuity. Subjects were instructed to read the sentences aloud as quickly and accurately as possible, and to read to the end of the sentence without correcting any errors. The time from start to finish of each sentence was measured with a stopwatch. Subjects continued reading the sentences down the chart until it was too small for them to read.

2. The paper version of the Contrast Visibility Indicator was used and minimum contrast level at which 5 figures were correctly identified recorded, as per Section 3.4.
3. The first of two head-mounted displays, introduced in Section 3.3, was presented to the subject and its mode of operation explained. The order of head-mounted display usage was predetermined and chosen at random.
4. The software version of the Contrast Visibility Indicator was run, as per Section 3.4.
5. The extent of visibility test was done, as per Section 3.5.
6. The reading test was run, as per Section 3.6.
7. The questionnaire was administered with regards to the first head-mounted display, as per Section 3.7.
8. Steps 3 to 7 were repeated with the second head-mounted display.

3.3 Head-mounted displays

3.3.1 Introduction

A review of previous research into using HMD systems in LVAs was made in Section 1.2. Devices used were often bulky and unwieldy, thus lacking comfort, and were indiscreet, making the user stand out when wearing it. Smart glasses are designed to overcome these issues. They aim to have a more familiar appearance by resembling spectacles, and to use miniature displays to be light and unobtrusive. By using transparent displays, the user is able to maintain visual contact with their environment. They are not yet readily available in the form of consumer products, and can be considered an immature technology, requiring further refinement in size, weight and quality. Nevertheless, models of smart glasses are available, often as developer kits, in order to trial them on patients.

Reference was made in section 2.3 to research on image processing techniques, aiming at the amelioration of vision, which are implemented on smart glasses. These few papers primarily investigated the image processing techniques they had developed, rather than the benefit conferred by the smart glasses themselves. The latter is, however, the aim of this chapter.

Thus far, smart glasses are a niche technology. Though they do offer unique features, they do so at a cost. Smartphones, on the other hand, are already owned by two thirds (66%) of UK adults, and, for the first time in 2015, surpassed laptops as the most widely owned class of internet-enabled device [2]. As described in section 1.2.2, a head-mounted display system can be made by mounting a smartphone into a headset with a pair of lenses. Such a device inherently suffers from the problem of bulk, referred to at the outset of this introduction. It does, however, offer a bright, large, hands-free screen for very little cost. It was therefore decided to investigate the smartphone headset in addition to the smart glasses, as this offers a 'budget' option. At the same time, it allows a comparison between opaque and transparent displays.

3.3.2 *Smart glasses*

The model of smart glasses used in the study was the Epson Moverio BT-200 (Seiko Epson, Japan); see Figure 3.1(a). It is comprised of two miniature high definition colour screens, one aligned to each eye, which then appear as a single virtual screen in the centre of the visual field with a field of view of approximately 23°. The screen appears at infinity. Therefore, when using the smart glasses, participants wore their distance glasses.

The luminance was measured through the lens at the position where the eye is placed using a Topcon BM-9 luminance meter (Topcon Technohouse Corporation, Japan). The luminance of a white and black screen on the smart glasses, set to maximum brightness, was measured to be 400 ± 50 cd/m^2 and 6 ± 1 cd/m^2 respectively. The large standard deviation arises due to the relative difficulty of measuring the brightness for the very small microdisplay screen.

As the smart glasses are partially transparent it was necessary to maintain a consistent background illumination level. A black background was chosen with a reflected luminance of 2 ± 1 cd/m^2. For comparison, the luminance reflected from the white page from which printed text was read was dependent on the angle at which it was tilted due to the light source being a ceiling bulb. It was measured as 70 ± 3 cd/m^2 when vertical but 92 ± 3 cd/m^2 when tilted 20° from the vertical towards the ceiling.

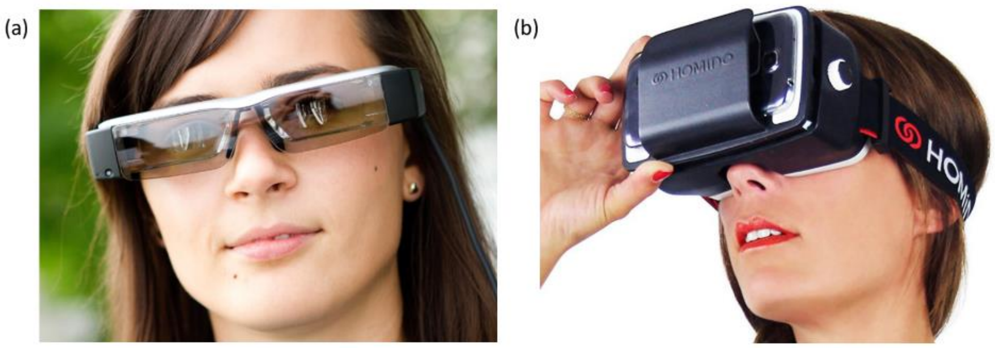


Figure 3.1. Devices used (a) Epson Moverio BT-200 with the lighter of the two neutral density filters [idnes.cz] (b) Homido headset with smartphone [homido.com]

3.3.3 Smartphone headset

For the other HMD system, a popular contemporary smartphone (2014) with a high pixel density of 538 ppi – the LG G3 (LG Electronics Inc., South Korea) – was chosen. The Homido headset (Homido, France), shown in Figure 3.1(b), holds the smartphone, uses a pair of lenses to magnify and image the screen, and helpfully includes a means to adjust the interpupillary distance. It includes three pairs of lens mounts that are chosen for normal, myopic or hyperopic vision. The optimal lens mount pair was chosen by each participant. The field of view is approximately 100° and the image appears close to the eye with a focal length of 4cm. At the phone's 80% brightness setting, as used in the study, the luminance was measured to be 190 ± 3 cd/m^2 for an all-white screen and less than 1 cd/m^2 for an all-black screen.

3.4 Contrast visibility indicator

3.4.1 Introduction

One of the symptoms of AMD is a loss of contrast sensitivity at high spatial frequencies [3]. As a consequence, discerning low contrast image features becomes more challenging. For a given display, it would be useful to measure the contrast level visible to a given user with visual impairment. This is especially the case for a partially transparent display, such as those on the smart glasses, where the background is changing and can reduce the contrast of the screen contents. This section describes the contrast visibility test upon which a computerized version is based, its computerized implementation and the results of using it on patients.

3.4.2 Contrast Visibility Indicator

The aim was not to measure the contrast sensitivity of the patient. To do this, the Pelli-Robson contrast sensitivity test would typically be used. Instead, what was needed was an indication of the level of contrast visible to the user on a particular screen. The Contrast Visibility Indicator, created by Hill & Aspinall, was chosen as the test to use.

The primary purpose of the Contrast Visibility Indicator is to assist patients optimise lighting conditions for near vision tasks by comparing their performance under controlled conditions to their performance at home. The extent to which good lighting improves reading may not be immediately obvious to the patient, particularly when adapting to a newly acquired disorder. The Contrast Visibility Indicator is a quick test that takes under a minute to complete. Being a simple, easily understandable test, it aims to encourage the use of adequate lighting.

The test uses the Landolt C optotype, also known as the Landolt broken ring or simply the Landolt ring. The Landolt C can be oriented at one of four angles, with the gap in the ring to either the right, left, top or bottom. The subject is asked to identify the orientation of the ring. This test is more typically used to measure visual acuity, with the size of the figures decreasing down the chart. In this case, however, the contrast of the figures decreases down the chart. It is available with white figures on a black background, and vice versa. The diameter of the Landolt C is 12mm.

The test uses a staircase procedure with two stages. In both stages, there are five figures at random orientations for a given contrast level. In the first stage, the figures decrease in contrast with a larger step size. This enables rapid identification of the approximate level of the participant. For the second stage the subject turns to the chart corresponding to the lowest contrast level at which they were able to identify the orientation of all five figures. The figures decrease in contrast with smaller step sizes thus enabling a more precise determination of contrast visibility.

3.4.3 Algorithm

As the time with the patient was short, an important factor in the design of the algorithm was speed. At the same time, accuracy was important so as to avoid false positives and false negatives. A secondary concern was precision.

The algorithm maintains the two stages which are present in the original paper-based test. Stage I has steps sizes of 10% in contrast, whereas the step size is 1% in Stage II. In the original test, there are 5 figures to each contrast level. With a paper-based test, there is the flexibility to move down the chart and start at an appropriate level, without going through all 5 figures of each level. In order to include this 'scanning' phase of the test, it was decided to divide each stage into two parts. The first part of each stage is the scanning phase, Phase *a*, where participants need only respond correctly to a single figure in order to move on to the next level. The second part is the verification phase, Phase *b*, where participants must respond correctly to five figures in order for that level to be considered as 'complete'.

The test generally only takes a few minutes to complete. The programme maintains both speed, by quickly cycling through levels to reach near threshold, and accuracy, by requiring five correct responses in order to consider a level as completed.

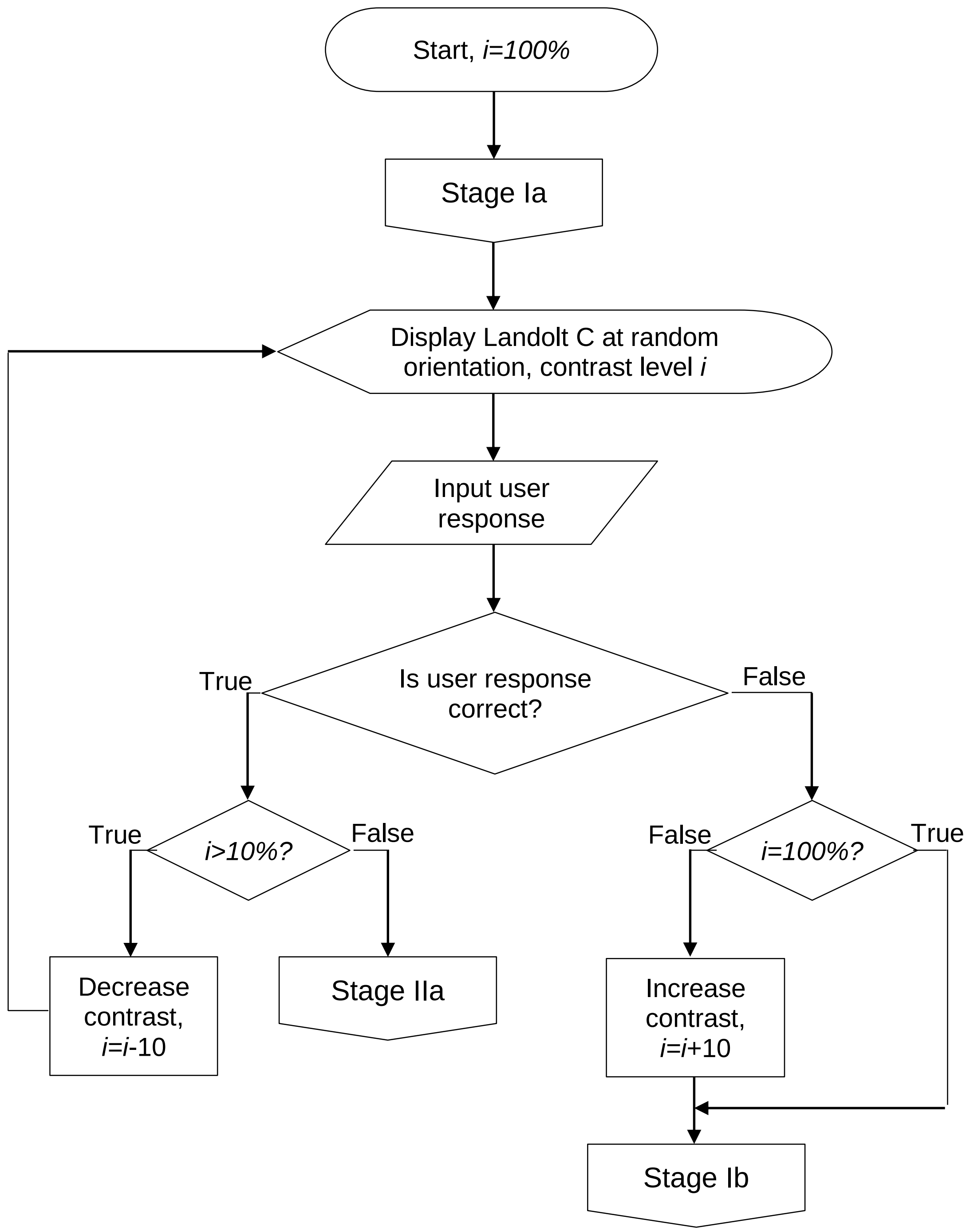
Figure 3.2 shows a flowchart of the algorithm created to fulfil these conditions. The test begins at Stage Ia, with the contrast, i, set to the maximum of 100%. Whilst the participant continues to response correctly, each subsequent figure is displayed with a contrast reduced by 10% until the contrast reaches 10%; at this point the test proceeds to Stage IIa in order to continue the scanning phase but with step sizes of 1%. If during

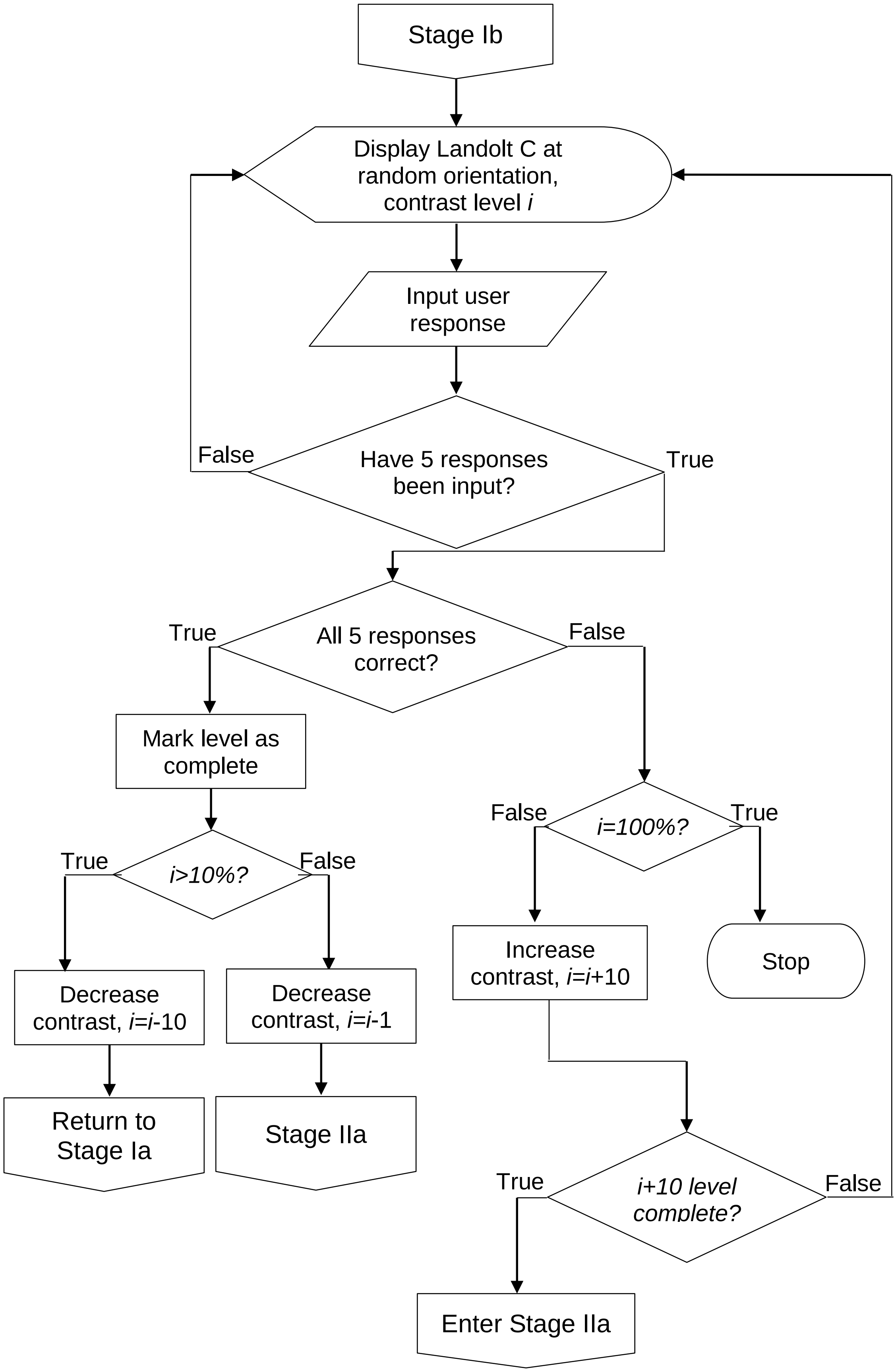
Stage Ia an incorrect response is given, the contrast is increased by 10% (unless already on maximum contrast) and verified during Stage Ib.

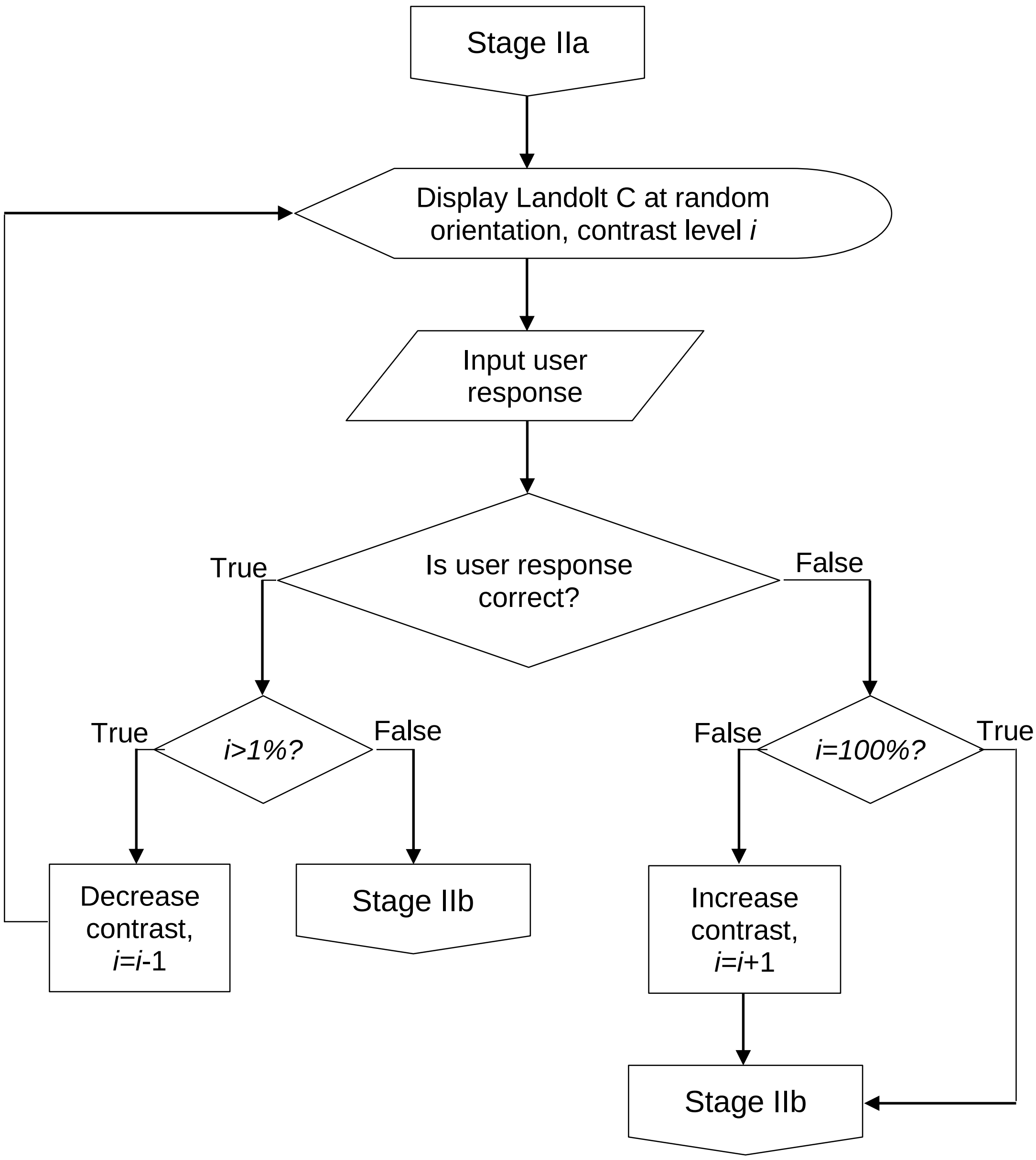
At Stage Ib, the figure is displayed five times at the same contrast level. If the responses are all correct, that level is marked as 'complete' and the test reverts to the scanning phase, Stage Ia if above 10% contrast and Stage IIa if below. If one or more responses were incorrect the previous level is verified, with two exceptions: If it is already on the maximum level, the test finishes; if the level at 10% above is marked as complete, then the 1% levels in between the completed and failed 10% levels are checked by proceeding to Stage IIa and beginning from the completed level.

Stage IIa proceeds as Stage Ia down to a minimum of 1%, at which point this level is verified at Stage IIb. An incorrect response also prompts the test to proceed to Stage IIb, verifying the level above.

As with Stage Ib, a level will be marked as complete when it has received 5 consecutive correct responses at Stage IIb. It will then move to the contrast level 1% down and move back to the scanning phase at Stage IIa, unless already on the minimum contrast level of 1%, in which case the test finishes with a result of 1%. The test will also finish if not all 5 responses were correct, but the previous level is marked as complete, and showing the result as the minimum completed contrast level. If the previous level is not complete it will move back to that level for verification, unless already at the maximum contrast level of 100%, in which case the test finishes.


Start, i=100%
Stage Ia
Display Landolt C at random orientation, contrast level i
Input user response
Is user response correct?
True
False
i>10%?
True
False
i=100%?
False
True
Decrease contrast, i=i-10
Stage IIa
Increase contrast, i=i+10
Stage Ib


Stage Ib
Display Landolt C at random orientation, contrast level i
Input user response
Have 5 responses been input?
False
True
All 5 responses correct?
True
False
Mark level as complete
i>10%?
True
False
Decrease contrast, i=i-10
Decrease contrast, i=i-1
Return to Stage Ia
Stage IIa
i=100%?
False
True
Increase contrast, i=i+10
Stop
i+10 level complete?
True
False
Enter Stage IIa


Stage IIa
Display Landolt C at random orientation, contrast level i
Input user response
Is user response correct?
True
False
i>1%?
True
False
i=100%?
False
True
Decrease contrast, i=i-1
Stage IIb
Increase contrast, i=i+1
Stage IIb

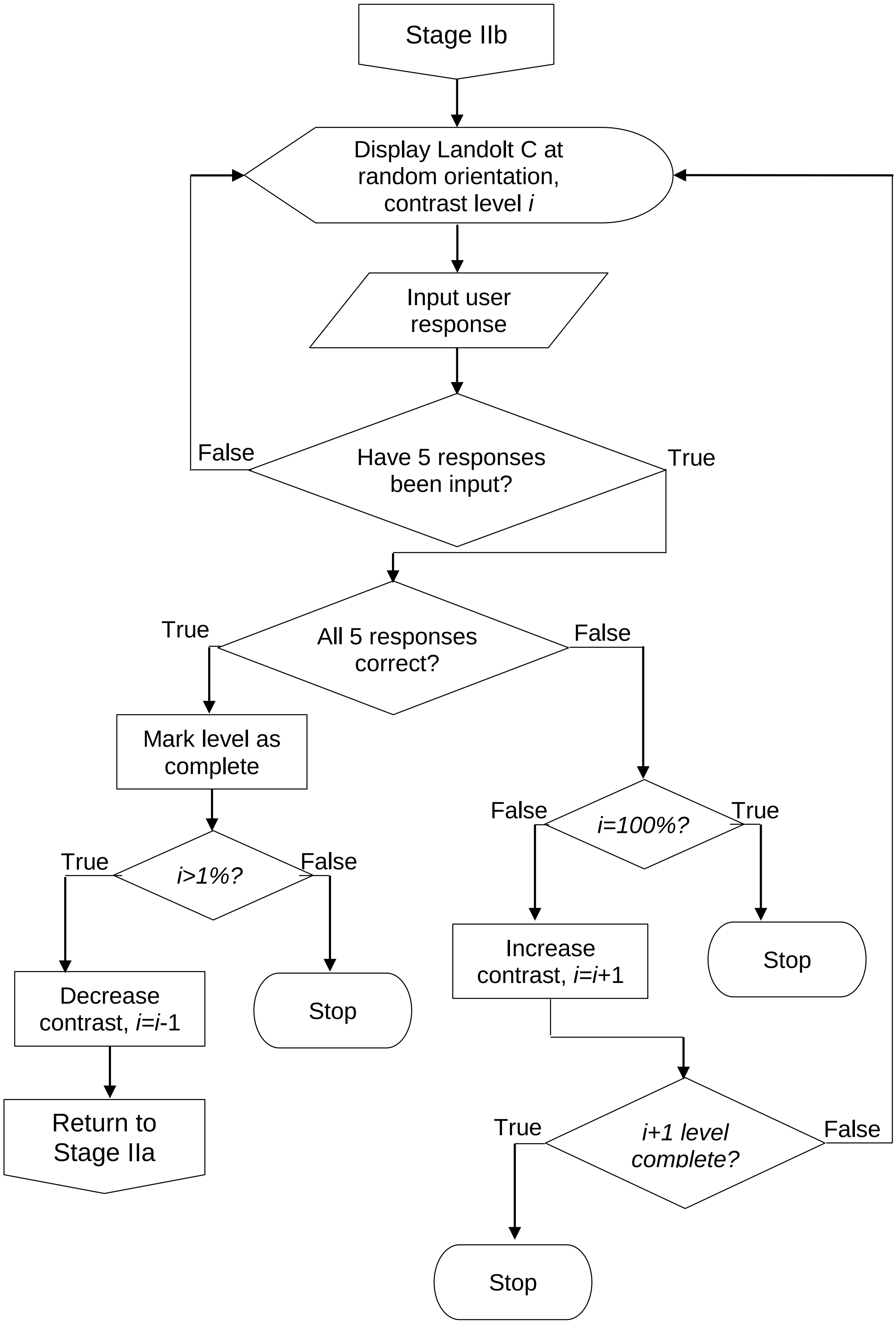


Figure 3.2. A flowchart of the algorithm used in the Contrast Visibility Indicator software. It is shown in four parts corresponding to the four phases of the algorithm, Stage Ia, Stage Ib, Stage IIa, Stage IIb.

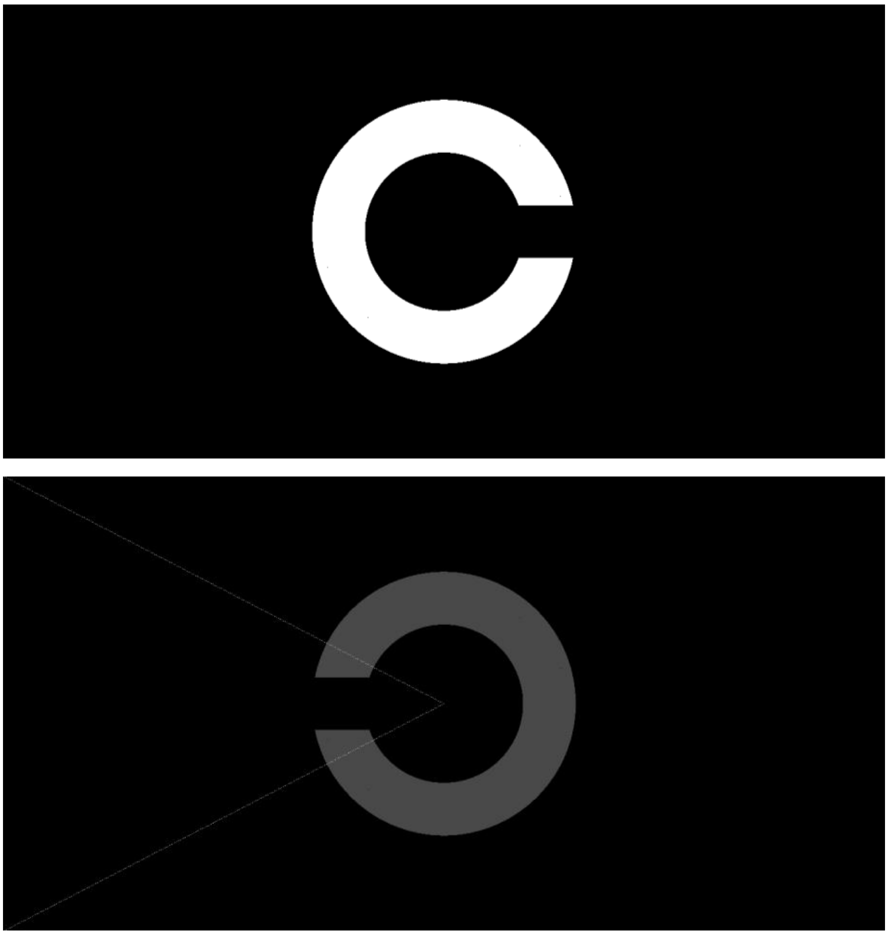
3.4.4 Graphical User Interface and control

During testing, a single Landolt C was displayed in the centre of the screen, as shown in Figure 3.3. A white figure on a black background was used to reduce eye strain and glare which those with AMD can be more susceptible to. This simple interface was used to minimize distraction whilst in testing. A separate screen, accessible before or during testing by pressing F1, contains the programme settings. These are the size of the Landolt C, either in units of font size or logMAR; the subject ID; and standard Kivy settings such as setting the window to full screen.

Both mouse and keyboard functionality were programmed; the selection of orientation could either be made through clicking the appropriate quadrant of the screen or by using the arrow keys. When selected, the quadrant would be outlined by a dashed white line in order to confirm selection.

The artwork on the welcome and results screens, as shown in Figure 3.4, was especially commissioned for the software. Created by Hannah Moshtael, it was inspired by the Landolt C figure.

(a)



(b)

Figure 3.3. Testing phase of the Contrast Visibility Indicator software. (a) The initial screen appearance, with the contrast at 100%. (b) Contrast reduced with the selection lines.

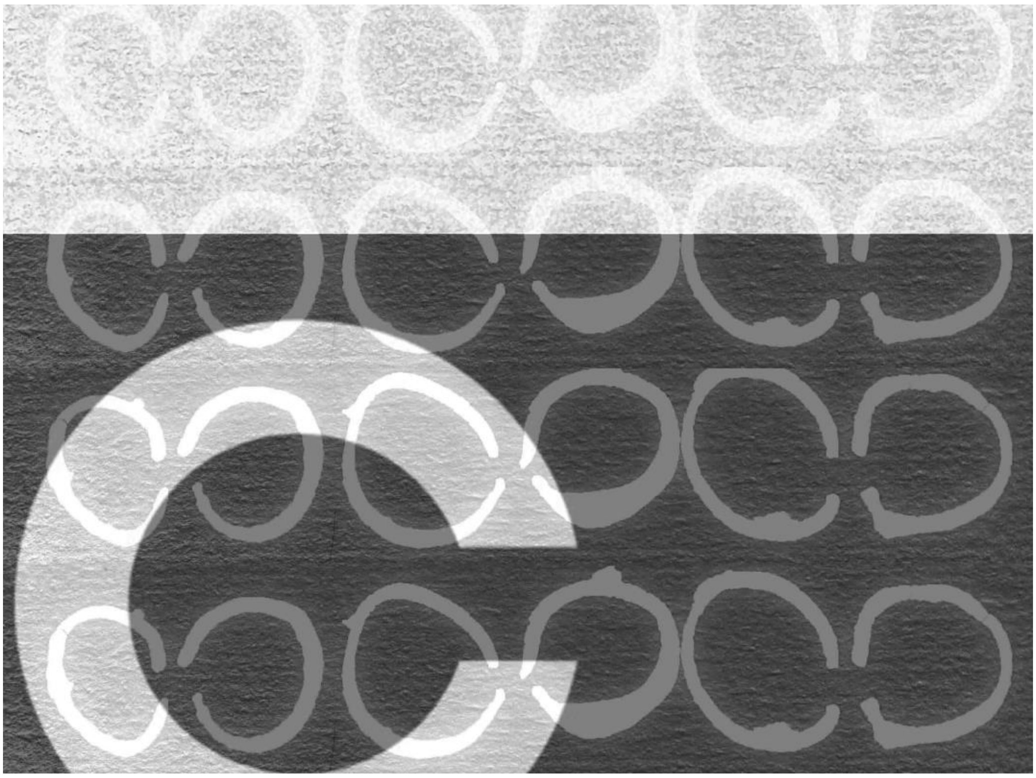


Figure 3.4. Artwork commissioned for the screen visibility tests. Created by Hannah Moshtael.

3.4.5 Patient trial results

The minimum contrast level at which the orientation of the Landolt C was correctly identified five times is shown in Figure 3.5 for each participant. Note that the minimum contrast level observable on the smartphone is lower, at 1%, than the smart glasses, at 2%.

As five of the eight participants observed the minimum contrast level, a ceiling effect was found for the smartphone. This means that, for these participants at this spatial frequency, the limit in the smartphone display to display low contrast was reached before the limit in the participants to view low contrast. Thus it would be expected that they would be able to view contrast on the smartphone as well as a normally sighted person.

Conversely, low contrast levels would be expected to be invisible to those who did not reach the lowest contrast setting. This is the case for all the participants viewing the smart glasses.

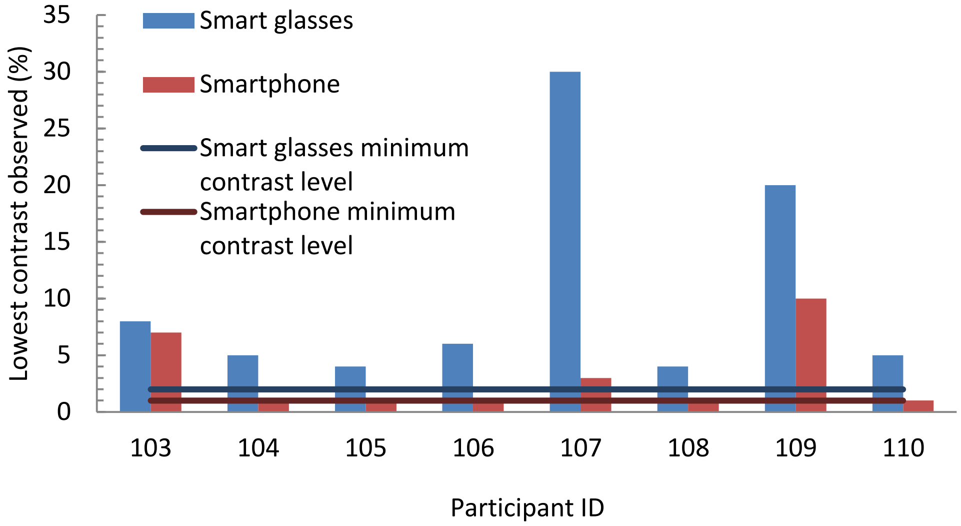


Figure 3.5. Minimum contrast level observable for each participant viewing the Epson Moverio BT-200 smart glasses, blue bars, and an LG G3 smartphone in a Homido headset, red bars. Horizontal lines indicate the minimum contrast that can be displayed which is 2% on the smart glasses, blue line, and 1% on the smartphone, red line.

3.5 Extent of visibility

3.5.1 Introduction

AMD involves the appearance and growth of scotomas in the central visual field. The smart glasses chosen for evaluation have a screen located in the central visual field. An important question, therefore, is how much of the display is visible to a user with AMD. We refer to the percentage of the screen seen by patients as the extent of visibility. In this section, we describe a test to perform this measurement.

The test is based on perimetry, the standard method for measuring the visual field. There are various types of perimetry, with the most common being automated perimetry [4]. It utilises a central fixation point such as a flashing light in order to encourage a steady gaze. A stimulus, such as a luminous point source, flashes at random locations in the field of view and the subject pushes a button when a stimulus is observed.

Our test does not aim to measure the visual field itself, but is a functional measure of the parts of the screen that are and are not visible to the subject. The result of the test is to produce a subject-specific visibility map of the display under investigation from which the extent of visibility is determined.

3.5.2 Graphical User Interface

A large flashing cross was positioned at the centre of the screen to act as a fixation point. As the subjects have macular disease, any centrally located figures need to be large enough so as not to be fully obscured by their central scotoma. The use of cross was chosen as even if the crossing point of the two lines of the cross is obscured, its location can intuitively be inferred from the direction of the lines. Other shapes could also be valid, such as a circle of square with subjects instructed to fixate at the centre of the shape.

In order to encourage the gaze to be maintained at this point, the cross was set to continually oscillate in brightness. A non-linear and non-sinusoidal shape to the oscillation was chosen from the Kivy library in order to lessen any hypnotic affects it might have which would detract from its aim of maintaining focus.

The stimuli which flash around this central fixation point are white dots, 5 arcminutes in diameter. The stimuli were displayed, one at a time, at randomly selected grid points for a duration of 300 ms. For the smart glasses, the grid points were evenly spread across the screen, in 5 rows of 6. For the smartphone headset, they were evenly spread across the central 60° field of view, in 5 rows of 5. The central location was not used in either case as this was where the fixation cross positioned. At 23°, the field of view of the smart glasses is small compared to the smartphone headset. Thus the entire smart glasses display would approximately fit within the central rectangle of grid points of the field of view of the smartphone headset.

3.5.3 Algorithm

In order for the test to run automatically, an algorithm was written to determine when and where the stimuli would be displayed, to respond to the user input, and to collate the results. It is outlined as a flowchart in Figure 3.6.

The test begins with the cross flashing in the centre of the screen and the participant instructed to fixate on it throughout the test.

It is necessary for the stimuli to appear at irregular time intervals in order to make them unpredictable and encourage the user to respond to what they see rather than any preconceived expectations. Therefore, at the beginning of each cycle, there is a window of time, the display window, within which the stimulus appears at a randomly selected moment.

After the stimulus is displayed there is a second window of time, the response window, in which the subject is expected to respond if they observe the stimulus. The speed with which subjects respond is assumed to vary, therefore a smart response window and display window were designed in order to adapt to the speed of response. This was implemented by recording all the response times and recalculating the average response time with each new data point. The response window, w_r, and display window, w_d, were then calculated by summing a minimum duration, $w_{r,min}$ and $w_{d,min}$, and the product of the average response time, t_r, and a multiplicative factor, x, according to equations 3.1 and 3.2.

$$w_r = w_{r,min} + xt_r \tag{3.1}$$

$$w_d = w_{d,min} + xt_r \tag{3.2}$$

The response window was initially set at 2 seconds and the display window at between 0.5 and 2.4 seconds from the start of the cycle. The minimum duration of the response window was 0.5 seconds and the display window 1.5 seconds. The multiplicative factor was 2.

If a response is made by the subject within the response window, that location is marked as observed. As is often the case with automated perimetry, a second chance is given when a stimulus is not observed the first time. Thus a location is marked as unobserved if the subject twice fails to respond.

The test continues until all locations are marked as either observed or unobserved. The duration of the test is between about 1 and 4 minutes.

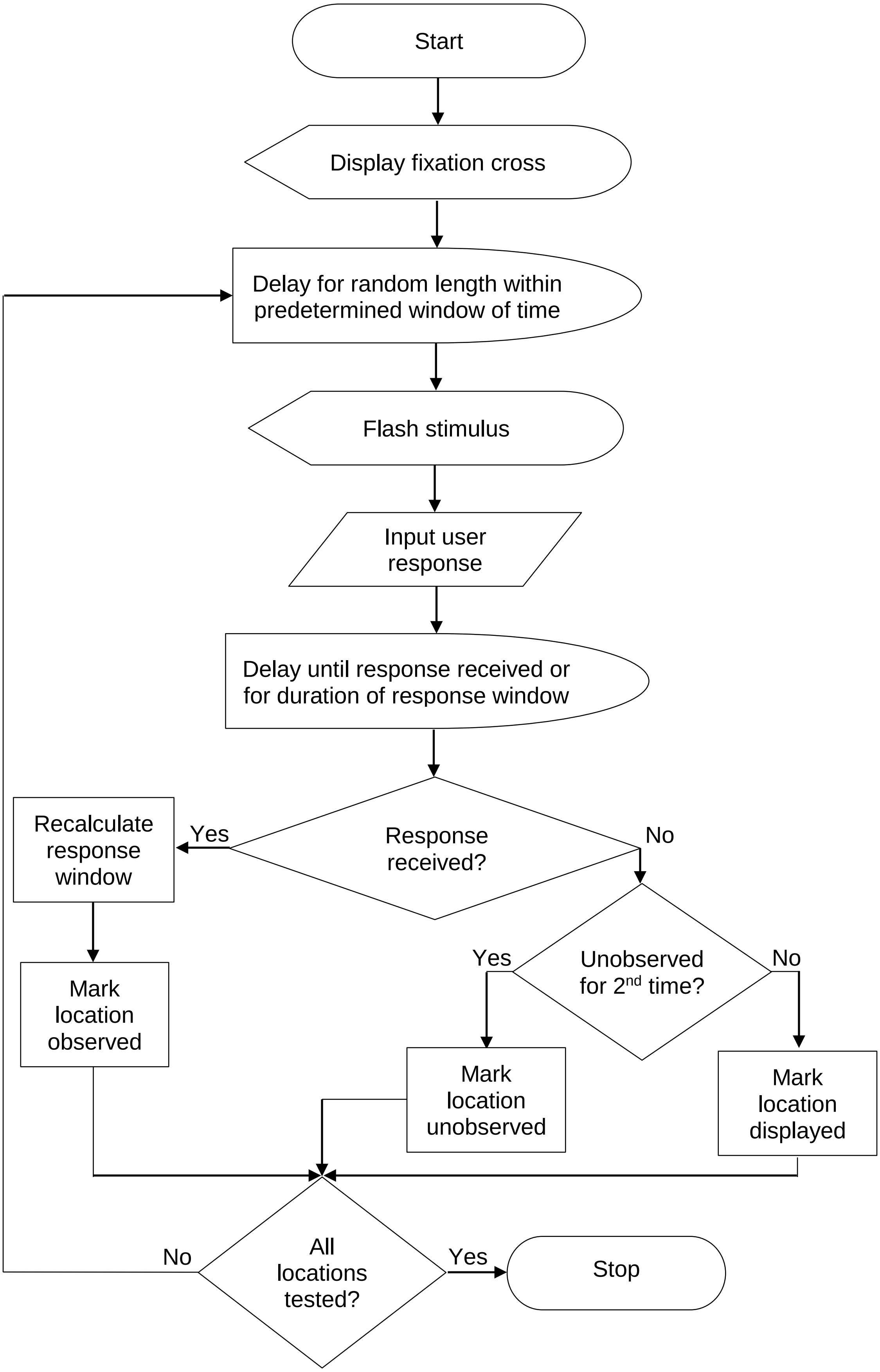


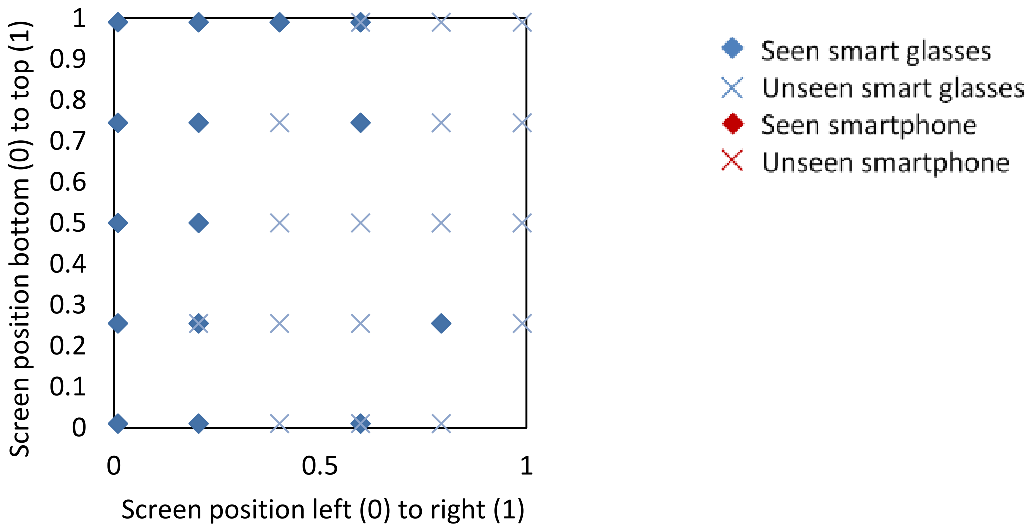
Figure 3.6. Flowchart of the algorithm used in the extent of visibility test.

3.5.4 Patient trial results

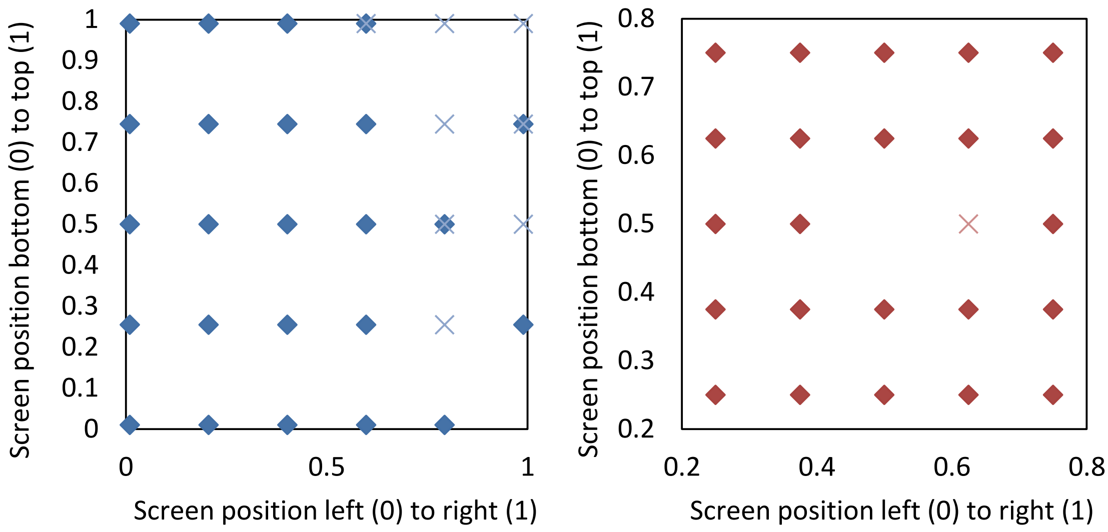
A unique profile was generated for each of the eight participants (103 to 110) who took the test. The extent of visibility of each screen to each participant was calculated as the percentage of points they saw. At least 45% of the points were seen on at least one display by all the participants, except participant 109 who saw just one point. All participants saw a higher proportion of points on the smartphone headset than they did on the smart glasses.

The pair of profiles generated from the test for each participant, one for the smart glasses and one of the smartphone headset, are shown in Figure 3.7. All the stimuli are shown, be it with a diamond to indicate a point that was seen, or a cross to indicate that it was not. A few stimuli are marked with both, meaning they were not seen on one occasion but were seen on the other. Note that the two plots would not be expected to match because they correspond with different screens of different fields of view (not directly with the retina of the patient).

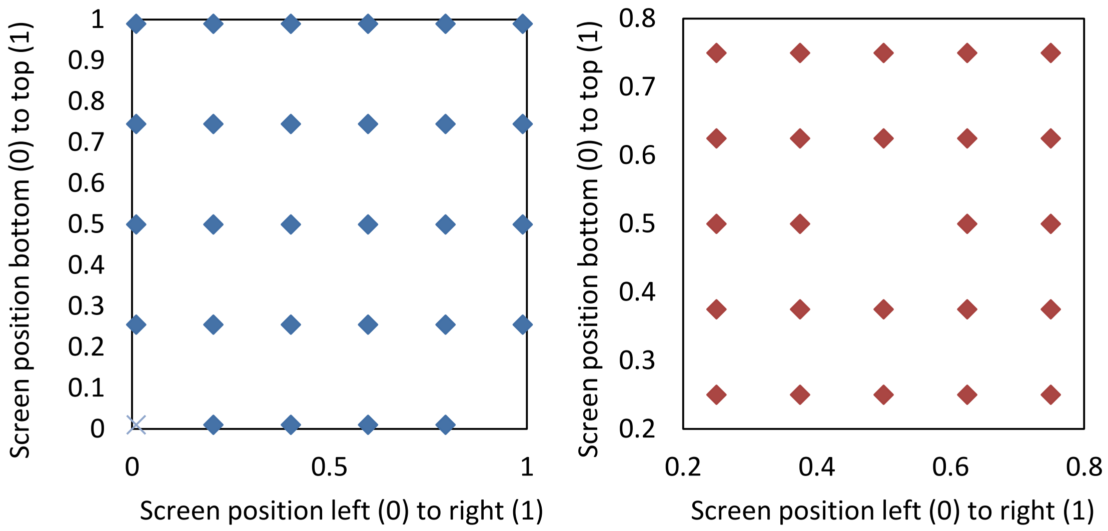
ID 103



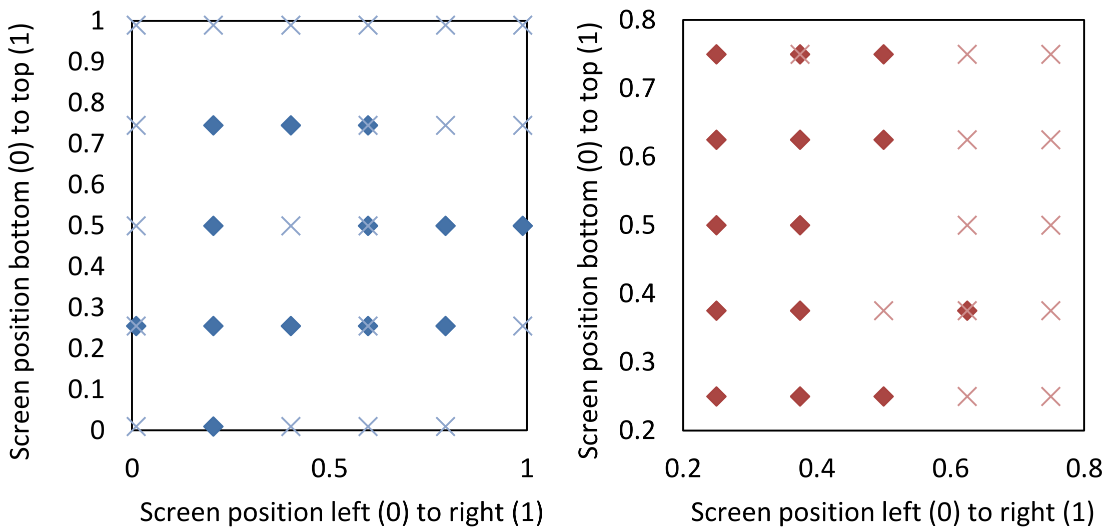
ID 104



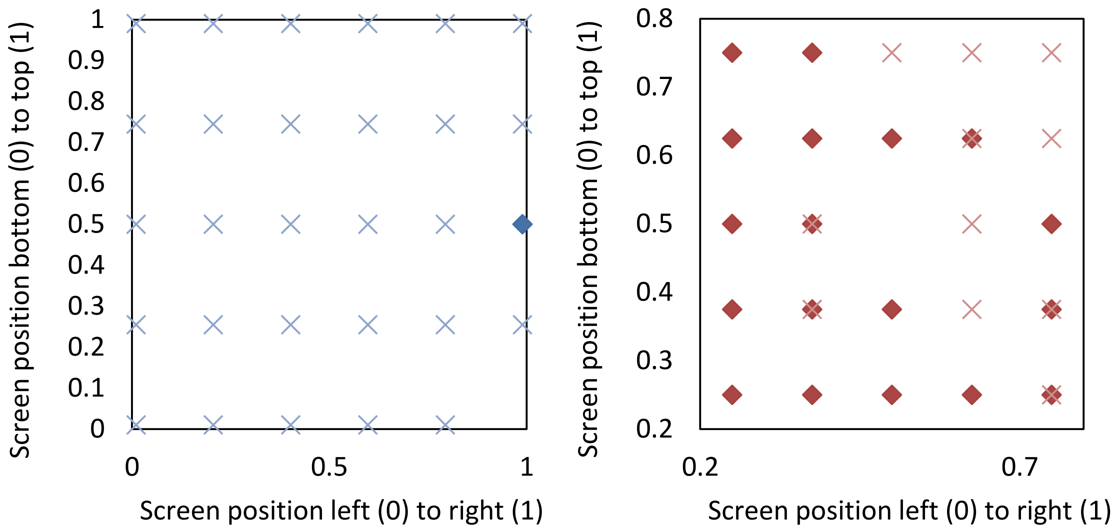
ID 105



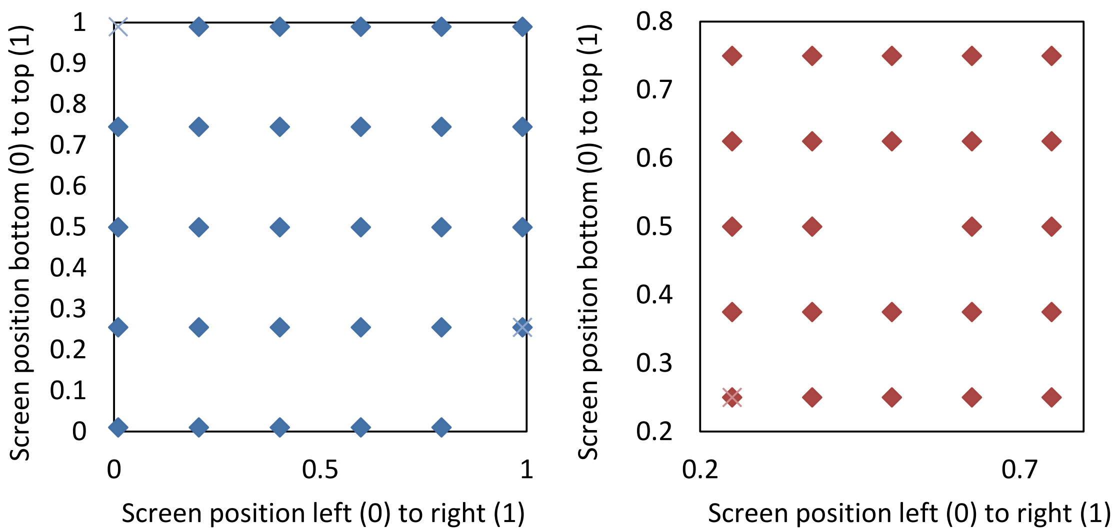
ID 106



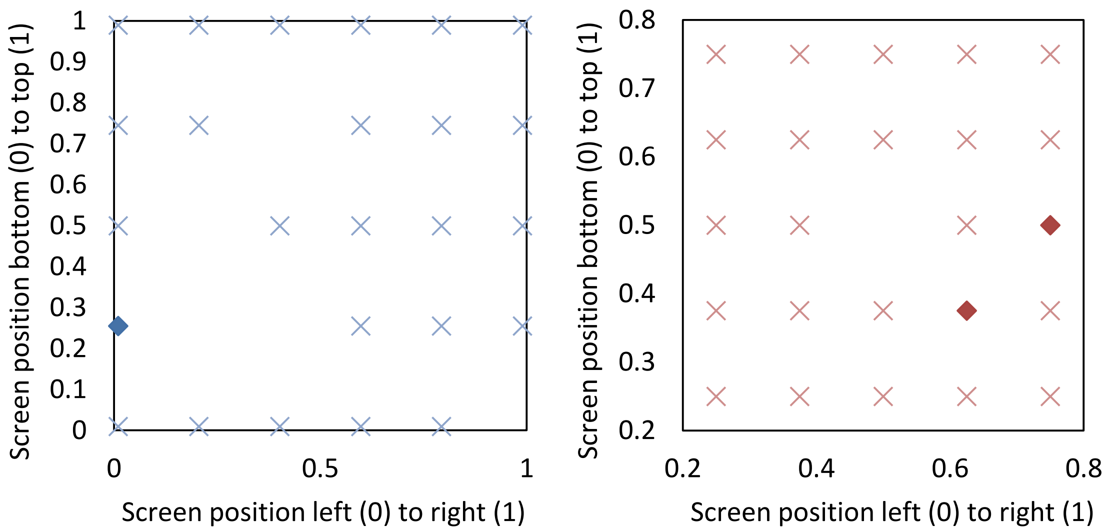
ID 107



ID 108



ID 109



ID 110

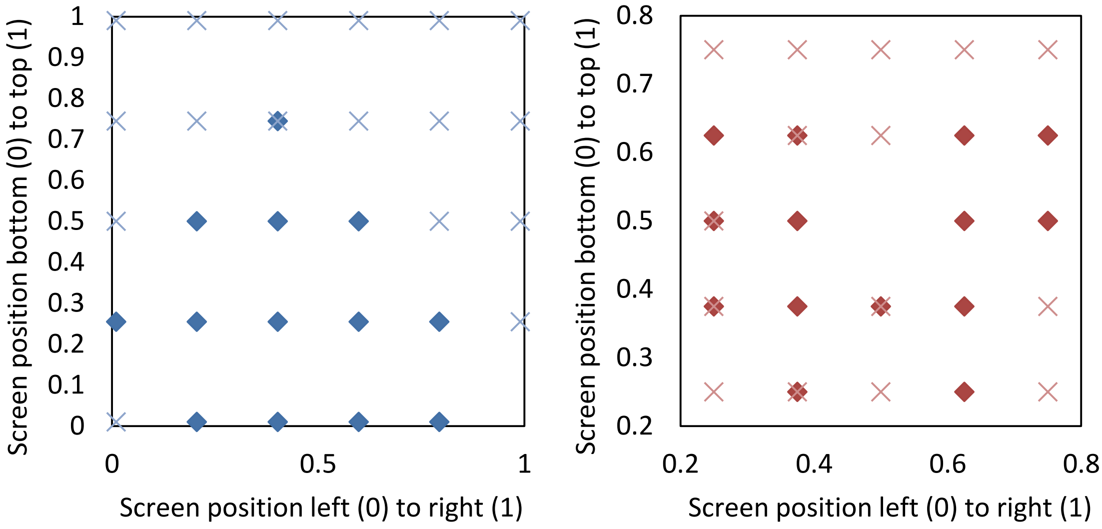


Figure 3.7. Results of the 'extent of visibility' test for each participant. Participants IDs are labelled, with the results from the smart glasses in blue on the left, and the results from the smartphone headset in red on the right.

3.6 Reading performance

3.6.1 Introduction

The final aim is to use head-mounted displays as a platform to improve reading in macular disease. It is necessary, therefore, to be able to measure reading performance on the head-mounted displays, and to compare it with reading from paper. Tests for measuring reading performance are commonly available in paper format, such as the MREAD Acuity Chart and the Radner Reading Chart, but also exist in electronic display format [5]. In order to make a comparison between paper and displays, it was decided to adapt the Radner Reading Chart for the head-mounted display. Permission was obtained from Wolfgang Radner.

There are 14 levels to the Radner Reading Chart, with letter size descending down the chart. Each level consists of a sentence standardized in terms of number and length of words, difficulty and syntactical construction [6]. Each 14-word sentence is spread across three lines. In total, there is a bank of 28 sentences. Permission was granted by Wolfgang Radner to use the sentences for our study.

For a valid comparison, the letter sizes on the display and on the chart must be equal. Therefore, size in millimetres or degrees subtended needs to be derived from the acuity chart units of Snellen acuity, logMAR, logRAD and M-units. These are defined and calculated below.

3.6.2 Visual acuity and reading acuity

Snellen created a new font, optotype, for his visual acuity chart, which is based on a five-by-five grid, as shown in Figure 3.8 [7]. For a given font size, the height and width of each letter is identical, and the stroke width is equal to one fifth of this length. He defined standard vision as the ability to discern optotypes that subtend 5 minutes of arc at 20 feet (6 metres), so that the stroke widths subtend 1 minute of arc. This gives rise to the familiar Snellen acuity ratio, *SA*, of 20/20 or 6/6. Other values of Snellen acuity are then expressed as a ratio of the individual's performance to the standard performance, where the denominator equals the distance at which the letter height subtends 5 minutes of arc, *d*, and the numerator equals the chart distance, *d'* [8], equation 3.3. The reciprocal of this ratio is the visual acuity, or the minimum angle of resolution (MAR).

$$SA = \frac{d'}{d} \tag{3.3}$$

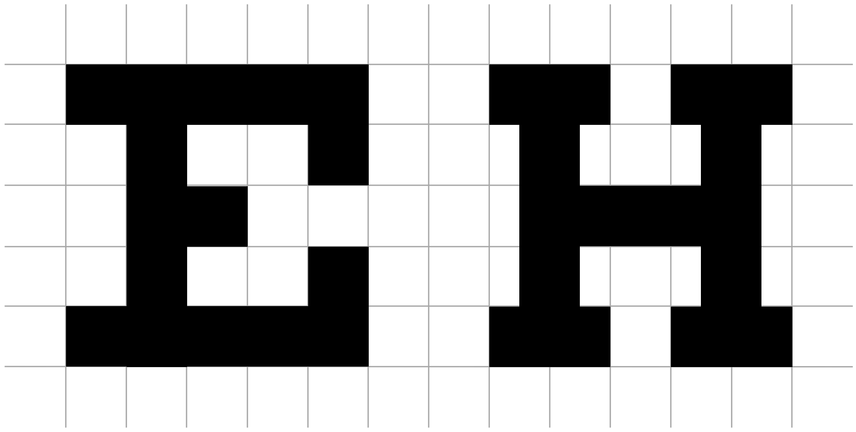


Figure 3.8. Snellen optotype of the letters E and H on a grid with units one fifth letter height.

Using simple trigonometry, d can be expressed in terms of the letter height in metres, h, where the tangent function takes degrees in equation 3.4.

$$d = \frac{h}{\tan\left(\frac{5}{60}\right)} \tag{3.4}$$

This gives an expression for Snellen acuity in terms of chart distance and letter height.

$$SA = \frac{d'}{h}\tan\left(\frac{5}{60}\right) \tag{3.5}$$

M-units provide a convenient way to describe letter sizes, where 1M equals the letter size which subtends 5 minutes of arc at 1 metre. Setting $d = 1$ in equation 3.4 gives a letter size of $h_{1M} = \tan(5/60) \sim 1.45$mm for 1M. Snellen acuity can thus be described in terms of the letter height given in M-units, M.

$$SA = \frac{d'}{M} \tag{3.6}$$

logMAR, the logarithm to base 10 of the MAR, is an equivalent measure of visual acuity. MAR is the angle in arc minutes subtended by the stroke width (a fifth of the letter height). As mentioned, the reciprocal of the Snellen acuity, *SA*, equals the MAR. Thus logMAR can either be calculated from the Snellen acuity or from the letter height and distance, as given by equation 3.7, with the result of the arctangent given in degrees.

$$logMAR = -\log_{10}(SA) = log_{10}\left[tan^{-1}\left(\frac{h/5}{d'}\right) \times 60\right] \tag{3.7}$$

On a Snellen Chart, all the letters have equal height and width and are uniformly proportioned in units of a fifth of their height. The Radner Reading Chart, however, aims to measure reading acuity and thus uses a common font, Helvetic. logRAD, the log reading acuity determination, is thus defined as a reading acuity measure and is equivalent to logMAR, a visual acuity measure. logRAD is calculated in the same way as logMAR, using equation 3.7, by using the height of a lower case “x” character as the letter height, h [9].

Print sizes on the Radner Reading Chart are logarithmically scaled and range from 1.3 to 0 logRAD when viewed at a distance of 25cm. A logRAD-Score is defined by the Radner Chart in order to assess reading acuity by taking account of errors. logRAD-Score is equal to the logRAD of the smallest sentence partially read plus 0.005 for each syllable incorrectly read.

3.6.3 Reading test on HMD

In order to compare reading on the chart with reading from the HMD, letter sizes on the HMDs that correspond with logRAD values on the chart needed to be calculated. As an HMD uses a virtual display, the text size was measured in terms of visual angle instead of letter height. For the smart glasses, visual angle of letters was calculated as a proportion of the total display field of view. This is 23° for the Epson Moverio BT-200 as specified by the manufacturer, but the Splashtop screen sharing app covered slightly less than the full screen on the smart glasses, a visual angle of 21.3°. By measuring the letter heights on the 39.6cm Samsung laptop from which the software was run, the visual angle of the letters could be calculated. The calculation for logRAD is thus simplified to equation 3.8, where the visual angle subtended by the letter height, α_{SG}, is given in arc minutes.

$$logRAD_{SG} = \log_{10}\left(\frac{\alpha_{SG}}{5}\right) \quad (3.8)$$

Letter sizes are set by the font size setting of the Kivy Python library used to develop the software. The relation between font size setting and letter height on the screen needed to be determined. A letter 'x' was displayed on a Samsung laptop screen with font sizes from 100 to 900 and the height measured. A linear relation between font size and letter height was found, as shown in Figure 3.9. Using the method of least squares, the gradient of the line was found to equal 0.01317 ± 0.00002, with a zero intercept to an uncertainty of 0.01. Thus the relation between font size, F, and letter height, h_l, is set according to equation 3.9.

$$h_l = 0.01317F \quad (3.9)$$

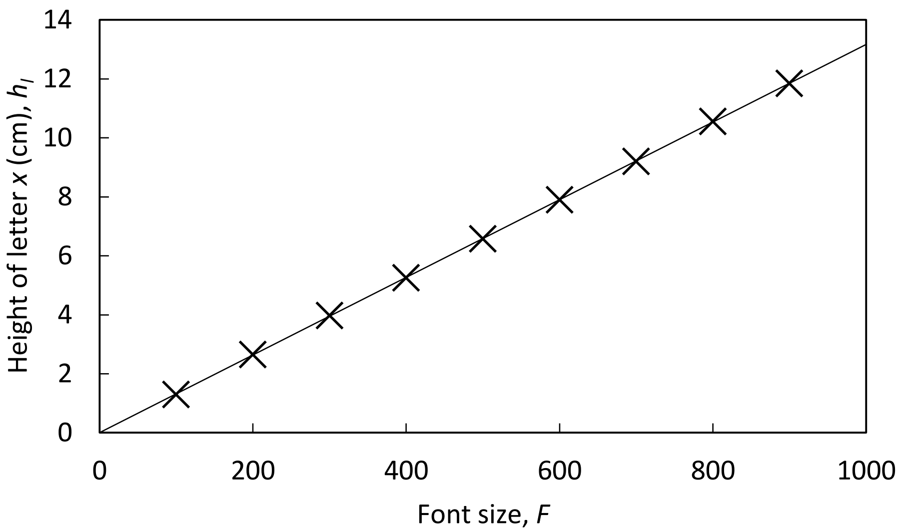


Figure 3.9. Relation between font size and letter height on a Samsung laptop.

The equation for logRAD can thus be written in terms of font size, F, instead of letter height. Setting F as the subject of the formula, in order to calculate the font size setting required for logRAD on the smart glasses, $logRAD_{SG}$, one obtains equation 3.10.

$$F = 11.77 \times 10^{logRAD_{SG}} \quad (3.10)$$

The smartphone based HMD is a simple magnifying glass optical system with the lens held at the focal length, 4cm, from the display. As the eye is positioned with negligible distance from the lens, the visual angle subtended on the display is given by simple trigonometry. The relationship between letter height on the LG G3 smartphone and font size setting was determined by measuring the height of a lower case 'x' for font size between 50 and 900. The results are given in Figure 3.10. Using the method of least squares, the gradient was calculated as 0.004596 ± 0.000007, with a zero intercept with an uncertainty of 0.004. The relation between letter height, h_S, and font size, F, is thus given by equation 3.11.

$$h_s = 0.004596F \tag{3.11}$$

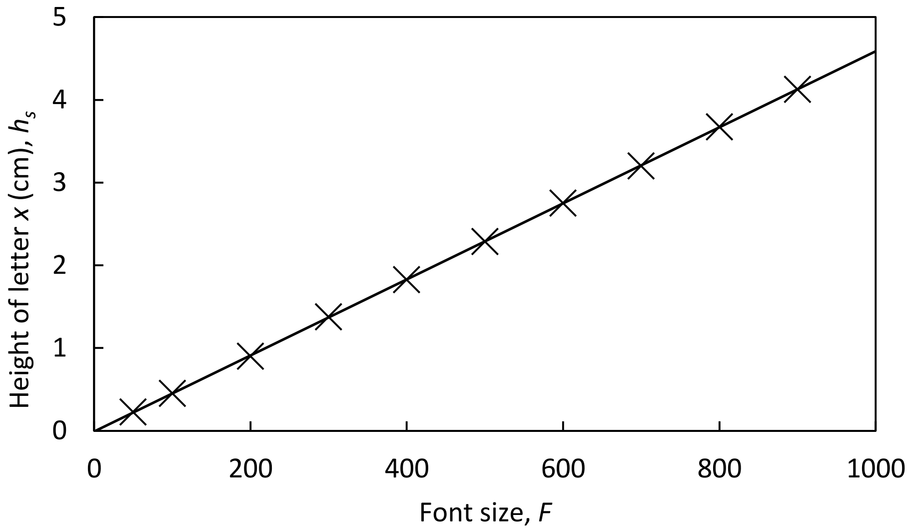


Figure 3.10. Relation between font size and letter height on LG G3 smartphone.

The relation between font size and logRAD on the smartphone headset, logRAD_S, is given by equation 3.12.

$$F = 1.3 \times 10^{logRAD_s} \tag{3.12}$$

A limitation to the smartphone-based system is that the smallest text size that can be displayed is 0.5 logRAD. This is because the smartphone display is highly magnified thus the text size on the screen itself has to be very small. Thus even a screen with a very high pixel density display such as the LG G3 used here, the stroke width of the letters at 0.5 logRAD is smaller than a pixel. A limitation of the smart glasses is the relatively small field of view. This means that a sentence with text size 1.1 logRAD or larger would not fit on the screen in the same format presented on the Radner Reading Chart.

Performance reading from the smart glasses and smartphone respectively were compared to performance reading from print. The English Radner Reading Chart, held at 25cm, was used to measure reading acuity and reading speed from print. Those who could not read the top line at 25cm were allowed to read from a distance of their choosing; this distance was then measured and the text size calculated accordingly.

3.6.4 Patient trial results

For a comparison between the three media of paper, smart glasses and smartphone headset, the participants' vision needed to be good enough to read at least the top line of the chart and poor enough not be able to read below the 0.5 logRAD limit set by the smartphone display. Five participants (102, 103, 104, 106 and 110) fit these criteria and were tested on all three media. Their results on each media are shown in Figure 3.11. The level of uncertainty, arising from the calculation of visual angle, was estimated at ±0.03 logRAD for the smart glasses and ±0.02 logRAD for the smartphone headset. For all five of these participants, the smart glasses allowed them to read the smallest text size. The mean and standard deviation in logRAD score for paper, smart glasses and smartphone headset are 0.8±0.4, 0.5±0.3 and 0.9±0.1, respectively.

To calculate the mean reading speed for a participant, the speed of reading 5 lines above their critical print size (the print size below which reading speed drops) was averaged together. There were five participants (103, 104, 105, 108 and 110) who read at least 5 lines for each media. Their results for each media are shown in Fig 3(b). The mean and standard deviation in words per minute on paper, smart glasses and smartphone headset are 123±7, 97±8 and 98±17, respectively.

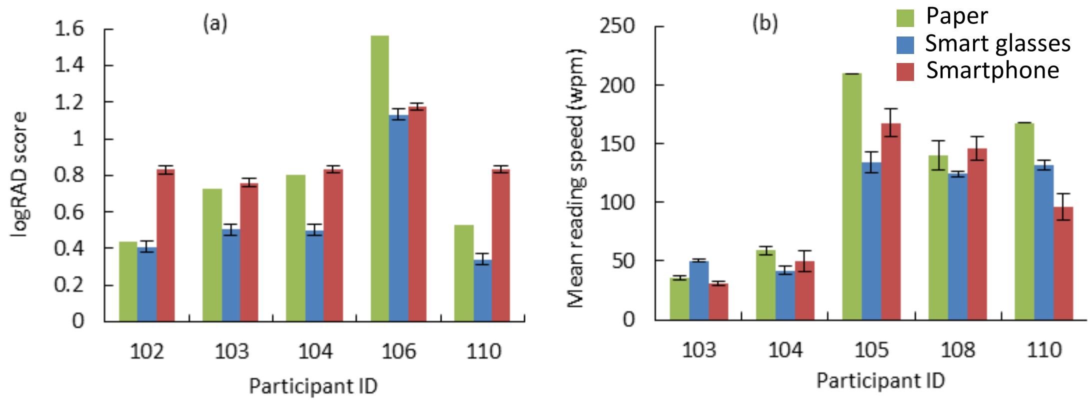


Figure 3.11. Reading performance. (a) The reading acuity for 5 participants, with error bars set at ±0.03 for smart glasses and ±0.02 for smartphone headset. (b) Mean reading speeds for 5 participants, with error bars indicating standard error.

3.7 Questionnaire

3.7.1 Introduction

Objective measures of visual function in using the head-mounted displays were collected to give insight into their potential for use by the partially sighted. To compliment such data, direct feedback from the patients themselves was needed. A questionnaire was written to collect this subjective feedback. A course entitled, 'Introduction to Questionnaire Design', offered by the Edinburgh Clinical Research Facility, was undertaken in order to be up to date with current methods.

3.7.2 Questionnaire design

Required data included both open questions for suggestions and comments to be taken, and closed questions in order to compare between participants. Questions were asked about three main subjects: The display they read from; the headset which they wore; and prospective use for a reading aid based on the head-mounted display. The questions are and choices for responses are compiled in Table 3.2.

The style and format of the questionnaire was based on a validated visual function questionnaire [10]. It was interviewer administered and was used in relation to a particular device.

Table 3.2. Questionnaire items and response options

	Question	Response options
The display	How easy did you find it to see the display?	Very easy / fairly easy / fairly difficult / very difficult
	Compared to reading large print from paper, did you find reading from the display to be...	Much easier / a little easier / the same / a little harder / much harder
	Did you prefer reading from the display or from paper?	The display / paper
	Do you have any comments on your experience viewing the display?	*Open question*
The headset	How comfortable did you find the headset to wear? Was it...	Very comfortable / fairly comfortable / fairly uncomfortable / very uncomfortable
	Based on the appearance of the headset, how comfortable would you feel to wear the headset at home? Would you feel...	Very comfortable / fairly comfortable / fairly uncomfortable / very uncomfortable
	Do you have any comments on your experience wearing the headset?	*Open question*
Prospective use	How likely is it that you would regularly use a head-mounted display like this to help you read?	Very likely / fairly likely / fairly unlikely / very unlikely
	What changes to the device, if any, would make you more likely to use it?	*Open question*
	Do you have any additional feedback?	*Open question*

3.7.3 Patient trial results

The proportion of responses to each option of the questions in the display category of the questionnaire are shown in Figure 3.12, Figure 3.13 and Figure 3.14. The number of responses to each option of the questions in the headset category are shown in Figure 3.15. The proportion of responses to each option from the prospective use category is shown in Figure 3.16.

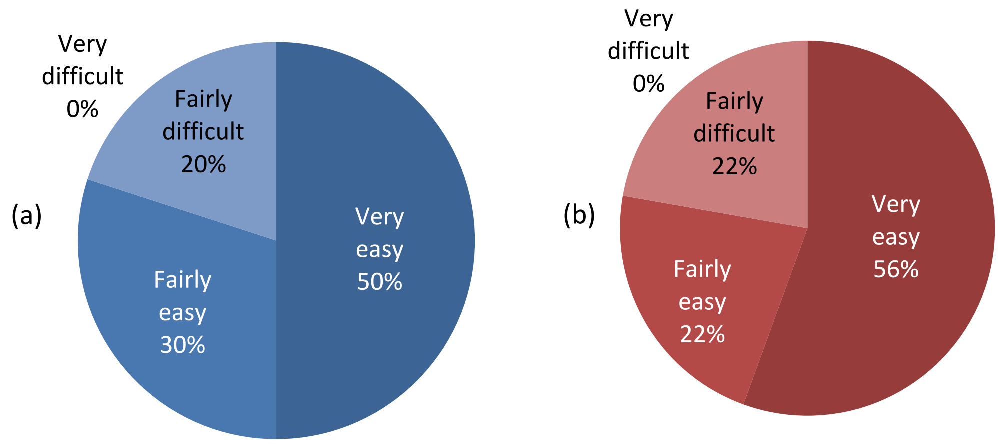


Figure 3.12. Responses to the question, ‘How easy did you find it to see the display?’

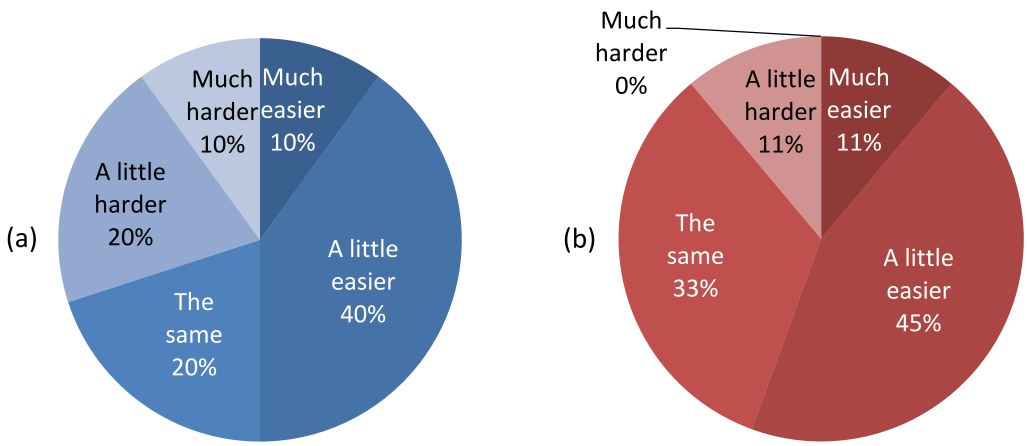


Figure 3.13. Responses to the question, ‘Compared to reading large print from paper, did you find reading from the display to be...’. Results for smart glasses on the left and smartphone headset on the right.

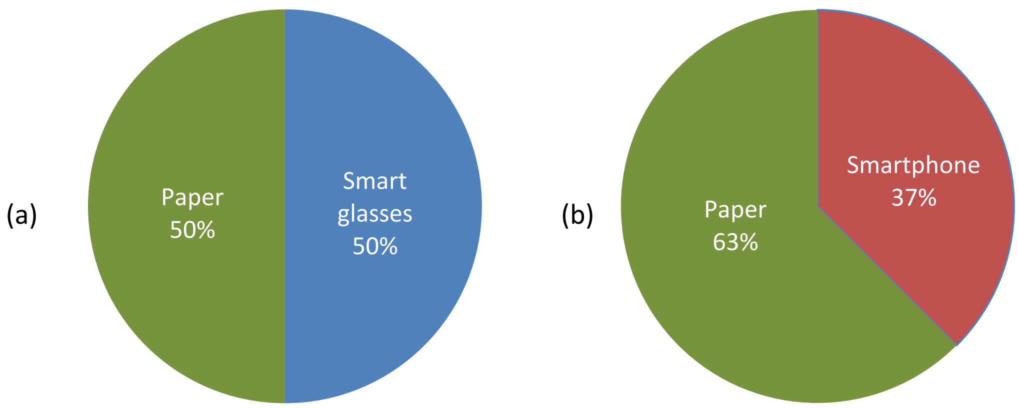


Figure 3.14. Responses to the question, ‘Did you prefer reading from the display or from paper?’, comparing with (a) smart glasses and (b) smartphone headset.

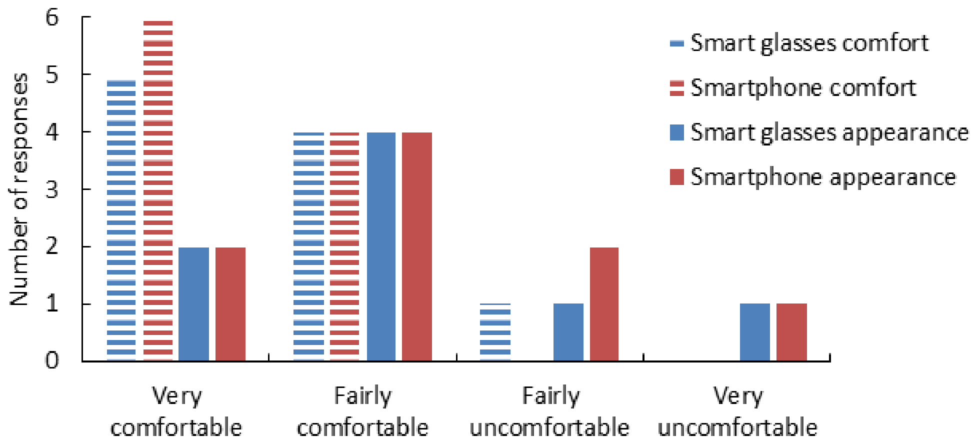


Figure 3.15. Responses to the questions, ‘How comfortable did you find the headset to wear?’ and ‘Based on the appearance of the headset, how comfortable would you feel to wear the headset at home?’.

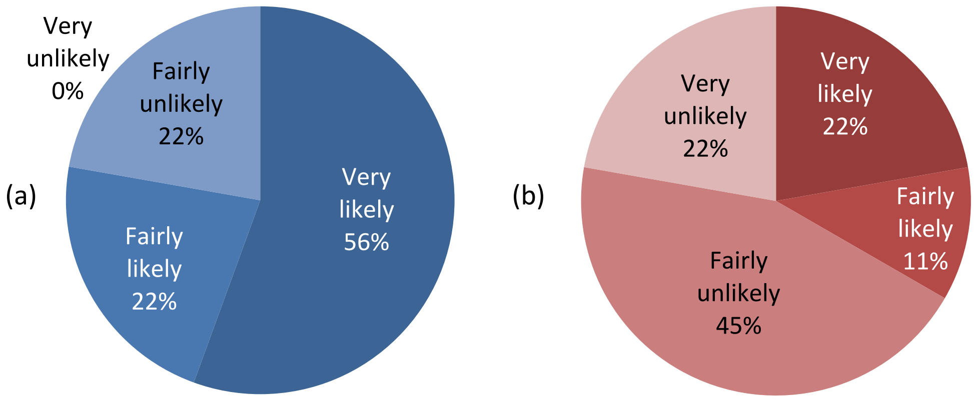


Figure 3.16. Responses to the question, ‘How likely is it that you would regularly use a head-mounted display like this to help you read?’

3.8 Discussion

3.8.1 Visibility of screens

A primary purpose of this chapter was to determine whether or not AMD would render these screens unusable. It may have been assumed, particularly for the smaller, centrally-positioned screen image of the smart glasses, that a central scotoma would almost entirely block the screen. However, in the extent of visibility tests, all but two of the participants saw at least 45% of the points on the smart glasses, and all but one on the smartphone. Also, all but one of the participants were able to read from both displays, including two out of three who were registered blind.

Analysing the results of these three participants more closely gives insight into the level of vision required for use of these displays. Participant 109 was the only to fail to read the top line of the reading chart at a distance of their choosing. This participant was, however, able to read from both displays. The participant who failed to read from either display was participant 107 who had the second worst reading acuity, with a logRAD-Score of 1.67. Both of these participants saw just a single stimulus in the extent of visibility test on the smart glasses, though participant 107 saw 75% on the smartphone display. The other participant who was registered blind was participant 106, who had a reading acuity of 1.56. This participant was, however, able to read from both displays and saw 45% of the stimuli on the smart glasses and 58% on the smartphone.

All the other participants were able to read from both displays and saw most of the stimuli. However, there is a large jump in reading acuity to the next participant, number 104 who had a logRAD-Score 0.8. The number of trial participants was too low to determine a precise reading acuity or extent of visibility threshold required for successfully viewing the displays. With all but one participant successfully reading from the displays, this trial suggests there is potential for both of these displays to be used by those with AMD.

3.8.2 Electronic display compared to paper

One point to emphasize with regards to the reading test is that, in this pilot, the text is being presented on the display in a print-like format – static, black-on-white and uniformly spread across the display. Clearly, if the aim was to enhance reading speed, then far more could be done to make better use of the additional capabilities of an electronic platform. Indeed, this was the next stage in the development process reported in subsequent chapters. However, even this basic display presentation method has its advantages over paper. A few participants described how these displays helped them read by removing background distractions and helping them concentrate on the text. The fact that displays are luminous would, no doubt, also have been of assistance. This would be a factor in the improvement seen in reading acuity from the displays. One reason the smartphone display may not have seen an overall improvement in reading acuity is that text size between 0.7 and 0.5 logRAD were included in the results, but were not perfectly rendered on the display.

The procedure used did not include practice time before the participants were timed to read sentences, which likely contributed to the average reading speed from both displays being slower than from paper. One participant stated, “If I got used to the headset I would prefer it”, citing their experience of becoming accustomed to their e-reader.

Although the text was rendered to subtend the same visual angle for each medium, our perception of size is related to our perception of the distance of the object. Viewing a virtual display confuses our perception of distance, particularly in the case of the smart glasses. One participant pointed out that when trying to read small print, established practice is to bring the print closer to the eye (and thus increase its visual angle). However, as the visual angle of the smart glasses display is fixed, viewing the display on top of a distant wall makes it appear large, but moving closer to the background wall makes the display appear to shrink.

This highlights another important difference between the media that a different participant highlighted: When using paper, the participants retained control over the page and could move, tilt or rotate it as they pleased (whilst keeping it at a distance of 25cm); but the HMD is held in a fixed position with respect to the head. This characteristic of the HMD may have contributed to the slower average reading speed from the displays, with one participant saying the smart glasses moved around a lot (with respect to the background) and another saying that the smartphone display was too close and they “wanted to take a step back”.

3.8.3 Smart glasses compared to smartphone headset

The smart glasses and the smartphone headset were rated almost the same in terms of both comfort and how comfortable they would feel to wear the headset at home, with both being on the positive side of the rating scale. Several participants additionally commented that they would not hesitate to wear the smart glasses outside too. As they smart glasses are more akin to spectacles, and the smartphone headset is bulkier, it is unsurprising the smart glasses rated well in these categories. A positive rating for the smartphone headset, however, suggests that their bulk is not unacceptable.

In terms of the questionnaire category relating to the display, the smartphone headset rated slightly higher in both subjective ease of seeing the display and subjective comparison with paper. This is likely to be related to the comparative brightness of the smartphone headset display, which, unlike the smart glasses, does not need to compete with background illumination. Despite this, the smart glasses rated higher when asked if they preferred reading from the display or paper.

3.8.4 Screen visibility tests

The three screen visibility tests aim to provide an indication of the level of visibility of a screen to a user, either in terms of level of contrast visible, spatial extent of screen visible or ability to read from it. Normally sighted users are able to see to the lowest contrast level, observe all of the stimuli across the screen and read text to the limit of the screen's resolution. The results are thus uniform. For the visually impaired participants, however, a range of results were obtained depending on the vision of the user. This shows that the tests were successful at distinguishing the needs of the partially sighted from the normally sighted.

An example result from the extent of visibility test is shown in Figure 3.7(b). It shows that the area of the screen to the left of the central fixation point was visible to the participant, whereas the area to the right was not. This participant is highly trained in eccentric viewing and thus aligned his preferred retinal locus, located in the top right of his vision, to the fixation point (rather than the fovea as for normal viewing). Consequently, his visual field was shifted towards the bottom left, thus partly accounting for the results. This emphasises how the results are relative to the fixation point.

None of the participants saw every stimulus of the extent of visibility test on the smart glasses. This suggests that individually tailoring the location of content displayed on the screen would benefit users with AMD. For instance, if one half of the screen was invisible to the user, content could be confined to the other half. Alternatively, a moveable fixation point could be used to direct the user to their optimal viewing location for the displayed content. Such a function would enhance the accessibility functionality of screen-based devices. Much more research is required to investigate this.

These tests achieved the purpose for which they were created, indicating the proportion of the screen available to the partially sighted users, and providing a comparison to reading from paper. In order to make them more robust, more thorough testing would be required to measure reproducibility, variability inter- and intra-tester and generalisability. Certainly, if they were to be adapted into computerised vision tests, like other recently developed tests for reading performance [11,12], contrast sensitivity [13] and visual field [14], they would need to meet validation criteria such as those set for measuring reading performance by Brussee *et al.* [15] and Rubin [5].

If the screen visibility tests were to be adapted into vision tests, standard testing conditions akin to those in a hospital would be needed. This would be difficult to achieve on the smart glasses which are strongly influenced by background illumination, but is conceivable on the smartphone headset which blocks out most ambient light. In addition to this, they would need to go through extensive validation in order to demonstrate that their results are comparable to the results of the gold standard vision tests.

3.9 Conclusion

This pilot study suggests that HMDs are acceptable to those with AMD and that this pathology usually leaves a high proportion of the screen visible for viewing and reading from. Their comments on prospective use, such as reading the news, labels on packets and buttons on the cooker, give insight into their challenges. A comment by a participant sums up an important factor in terms of prospective use: “If it made me see more, I’d use it!”

Average reading speed was higher using paper than the displays for the static, print-like text investigated in this trial. The following chapters will consider how to best utilise this platform to increase reading speed in AMD beyond the levels achieved with paper.

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CHAPTER 4

Biomimetic or Saccadic Scrolling: Speed Reading Strategy Based on Natural Eye Movements

This chapter is adapted from the paper, 'Saccadic Scrolling: Speed Reading Strategy Based on Natural Eye Movements', of which I am the lead author, published in peer-reviewed conference proceedings by IEEE and reproduced with permission of authors and publisher [1].

4.1 Introduction

4.1.1 Introduction

Eye movements while reading have been studied for decades, particularly with the advent of high accuracy eye-trackers [2]. This research has led to a much greater understanding of the psychology of reading. The aim of this chapter is to apply this knowledge on reading to develop a new reading strategy. This could be considered a biomimetic (or psychomimetic) approach to engineering, as it uses a natural approach as the basis for an engineered approach [3]. We refer to this strategy, therefore, as biomimetic scrolling.

In our paper presenting this research [1], we referred to this method of text presentation as saccadic scrolling because it mimics the saccadic movements of the eye. It was explained that this term had already been coined by Sekey & Tietz in 1982 [4] but that the method they describe would now be referred to as sentence-by-sentence presentation. We thus felt saccadic scrolling would be a suitable term to use for our method. Therefore, both saccadic scrolling and biomimetic scrolling can be used interchangeably. In this thesis we use the latter term.

The chapter begins by reviewing the main features of the theory on eye movements whilst reading. Background is then given to various forms of text presentation and the benefit these forms have for the visually impaired. After presenting the details of the eye movement corpus which was used to analyse natural eye movements, a description of the features of biomimetic scrolling is offered. This includes two aspects – a direct translation of eye movement into text movement in section 4.3, and a text movement strategy based on the eye movement theory in section 4.4. Finally, the methods and results of a reading speed study are given that compares biomimetic scrolling to other methods of text presentation.

4.1.2 Eye movements whilst reading

The purpose of eye movements in reading is to direct the light from the target words onto the fovea, the area of the retina with the highest visual acuity, as described in Section 1.1.2. Figure 4.1 schematically illustrates the rapid drop in visual acuity away from the point of fixation and thus the need to move the gaze across a line of text in order to read it.

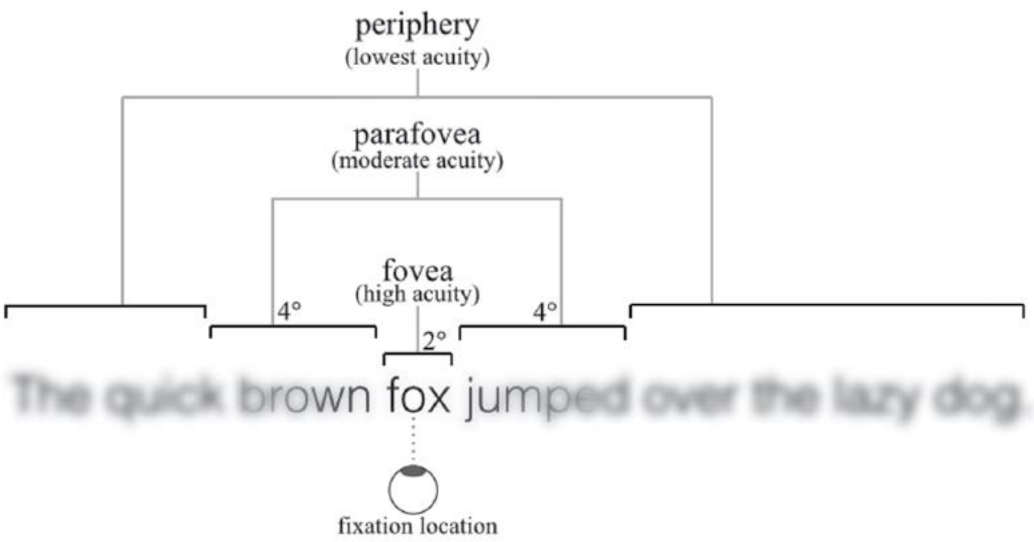

Figure 4.1. An illustration of the visual acuity across the retina as compared to a line of text, assuming a fixation location in the middle of the word ‘fox’. Reproduced from reference [5] with permission from SAGE Publications.

Contrary to subjective impression, the eyes do not move smoothly across a line of text whilst reading. Rather they move in short, rapid steps called saccades, then fixate briefly in a particular location before making the next saccade. The eye movement data that is output from eye trackers is typically analysed by categorising the data points into saccades and fixations.

A saccade causes the world to pass by at speed. However, we do not subjectively notice this due to an effect termed saccadic suppression. This stabilises the perception through a reduction in visual sensitivity when a saccade is made [6]. As no useful information is acquired during saccades due to saccadic suppression, it is during fixations that visual information is received [7]. Lexical processing does, however, continue during saccades [8].

Fixations typically last around 250 ms, but there is considerable variation depending on text legibility, linguistic difficulty, reading ability and the aim of the reader [5]. Saccades are much shorter, with forward saccades typically lasting around 20 to 35 ms and spanning 7 letters for English [5].

Not every word is fixated. There is a probability, p_0, that the word (or the space preceding it) will be skipped, a probability, p_1, that it will be fixated once and a probability, p_2, of refixation (more than one fixation). These three probabilities sum to unity. Three principal word-based variables determine these probabilities for a given word: Word length, word frequency (how common the word is), and word predictability [9].

Saccades are not always forward. Backward saccades are referred to as regressions and they occur about 10% to 15% of the time [10]. They are an important part of reading and are used for various reasons, such as correcting oculomotor mistakes and increasing linguistic comprehension [11]. The total viewing duration is the sum of all fixation durations on a word, regardless of whether they are regressions or not [12].

4.1.3 Presentation of text

Reading on-screen electronic text is one of the most widespread and significant human-machine interactions [13]. Early in the process of electronic screens replacing traditional reading media it was recognised that the presentation of text need not follow the constraints of paper and alternative forms of presentation may be more desirable [14]. The more recent proliferation of miniature direct-view display screens, in devices such as smartphones and smart watches, has renewed interest in alternative methods of text presentation to the traditional page-at-a-time display [15].

Several formats of text presentation and reading that have been proposed by Castelhano & Muter [16] are summarized as follows: a moving window display, with normally formatted text being moved into view; leading or times square (named after Times Square in New York City) which is continuously scrolling text; line-stepping, similar to times square but the text is stepped in discrete parts; sentence-by-sentence presentation which displays individual sentences; and rapid serial visual presentation (RSVP), in which single words are displayed in quick succession at fixed location on the screen.

RSVP is known to allow rapid reading as it removes the need for eye movements [17]. Variations and refinements on this technique have been introduced. By way of example, an RSVP app called Spritz centres and highlights the letter at the optimal recognition point of a word, displays longer words for a longer time and increases the pause length at the end of sentences [18]. A completion meter, a graphical representation of progression through the text, has also been suggested to provide an alternative to the normal visual cues [19].

However, an intrinsic feature of this method is that it suppresses parafoveal processing. This is the term given to the way readers use their off-central (parafoveal) vision to access information from words before reaching that part of the sentence [10]. It has been demonstrated that this, along with the prevention of regressions [20], adversely affects comprehension during RSVP reading [5,18,21].

Continuously scrolling text, as it displays sentences rather than single words, has been shown to maintain the benefit of parafoveal preview used in normal reading [22]. However, it requires smooth pursuit eye movements which are not required in normal reading, and increases fixation/pursuit time compared to the static condition [22,23]. When scrolled too quickly the words appear blurred and become difficult to read.

The novel method of scrolling we describe in this chapter could be considered a smart form of line-stepping. Line-stepping was first mentioned in 1974 [24], and one study found similar comprehension rates with line-stepping and RSVP [25]. It has been recognised that by fixating on a point, line-stepping simulates a series of fixations and saccades [26,27]. However, there are no reported strategies of text display which attempt to make the movement of text mimic eye movements. Our method intends to combine the benefit of speed reading present in RSVP with the benefit of parafoveal preview present in scrolling.

4.1.4 Text presentation for the visually impaired

Those with central vision loss often benefit from using a strategy for reading that differs from the fovea-centred strategy of normal reading. Section 1.2.1 described eccentric viewing which involves adopting a preferred retinal locus (PRL) to act as a pseudo-fovea, thus utilising a healthy area of the retina instead of the damaged macula. A technique that is often used in conjunction with eccentric viewing is steady eye strategy. This involves keeping the eyes steady, fixating on a particular point, and moving the text across this point. This is, in a sense, the inverse of regular reading which keeps the text steady and moves the gaze across the words.

Electronic text display can be used to ease the implementation of these strategies. Scrolling text in a horizontal line across the screen provides an alternative to moving a page of text across a steady gaze, required in the steady eye strategy. An iPad app was developed with this in mind, enabling on-line control of speed and reversal of direction [28]. A recent study with 17 participants reading eccentrically with a simulated central scotoma found reading accuracy and adherence to eccentric viewing strategies improved reading scrolling text compared to static text [29]. An earlier study found that the reading speeds increased by around 15% for scrolling text compared to the static condition for a population of 24 low vision participants [30,31].

RSVP has also been investigated for its benefit to increase the reading speed of the visually impaired. As this method requires just a single point of fixation, this method reduces the need for high oculomotor control which is especially beneficial for those using a PRL. A study on 35 low vision participants (most with central field loss) compared RSVP, horizontal scrolling, vertical scrolling and static text presentations [32]. It found no significant difference in maximum oral reading rates between the four conditions, and that half of low-vision subjects preferred the horizontal scrolling format. Another study found text needed to be eight times acuity threshold before RSVP showed a benefit for low vision participants [33]. Varying the duration of display for each word based on its length was found to increase reading speed in participants with age-related maculopathy [34]. Another study investigated RSVP as a training strategy to read text in static page format [35]. The median reading speed of 18 participants with juvenile macular dystrophy increased from 83 wpm before training to 104 wpm afterwards.

Those whose sight deteriorates in later life have been reading in the standard way, described in section 4.1.2, all their life. To learn to read in a new way at this age will clearly have its challenges. But what if the presentation of text appears to them in the way it has appeared to them all their life, as a series of fixations and saccades? Could this improve their reading? This was the question that motivated the research reported in this chapter.

4.2 Eye movement corpus

4.2.1 Introduction

An eye movement corpus was made available to us by Antje Nuthmann of the University of Edinburgh in order to investigate biomimetic scrolling. This section describes the methods of collection of this data and how it was analysed to identify fixations and saccades.

4.2.2 Materials and design

Each participant read the same 150 single sentences [36]. Sentences averaged 12 words in length (range = 7–16). Each sentence was presented on a single line and had a mean of 68 characters (letters and spaces, range = 55 to 80).

4.2.3 Participants

40 young adults who were students at the University of Edinburgh and 27 older adults from the community participated in the eye-tracking reading experiment. The young adults (7 men and 33 women) averaged 22.2 years of age (range = 18 years to 29 years), and the older adults (14 men and 13 women) averaged 72.7 years of age (range = 66 years to 83 years). All participants had normal or corrected-to-normal vision.

4.2.4 Apparatus

Eye movements were recorded with an SR Research EyeLink 1000 Desktop mount system. It was equipped with the 2000 Hz camera upgrade, allowing for binocular recordings at a sampling rate of 1000 Hz for each eye. Data from the right eye were analysed. The experiment was implemented in SR Research Experiment Builder.

4.2.5 Procedure

Participants pressed a button on the controller once they finished reading the sentence. To ensure that subjects read the sentences and not just moved their eyes, 30 randomly selected sentences were followed by an easy comprehension question, requiring a three-option response.

4.2.6 Analysis

Gaze raw data were parsed into sequences of fixations and saccades using SR Research Data Viewer, using the default parameters. Those data were converted into an interest area report, which provides a columnar output of eye movement data for each word in a sentence, separately for each participant.

4.3 Reverse engineering individual gaze movements

4.3.1 Introduction

This section presents an analysis of the eye movement corpus. It describes the method used to directly translate eye movements into text movements.

4.3.2 Reading eye movements

For a given sentence, there is a unique pattern of fixations for each individual reading it. In order to visualise these fixations, and to compare between different individuals reading the same sentence, the fixations were plotted relative to the sentence. One of these plots, for one of the sentences, is shown in Figure 4.2. The markers used on this plot are numbers which correspond to the order in which the fixations were made. The positions of these markers is the horizontal position of fixation relative to the sentence displayed. The other axis separates participants, and the colour differences of each line further assists to differentiate participants. Thus the fixation positions of each participant can be viewed side-by-side, allowing a visual comparison between individuals.

Figure 4.2 depicts all of the fixations on this sentence made by all 27 of the participants in the older category of the eye movement corpus, in the order they made them. No clear pattern is discernible amongst participants. This illustrates the great variability among individuals reading the same sentence.

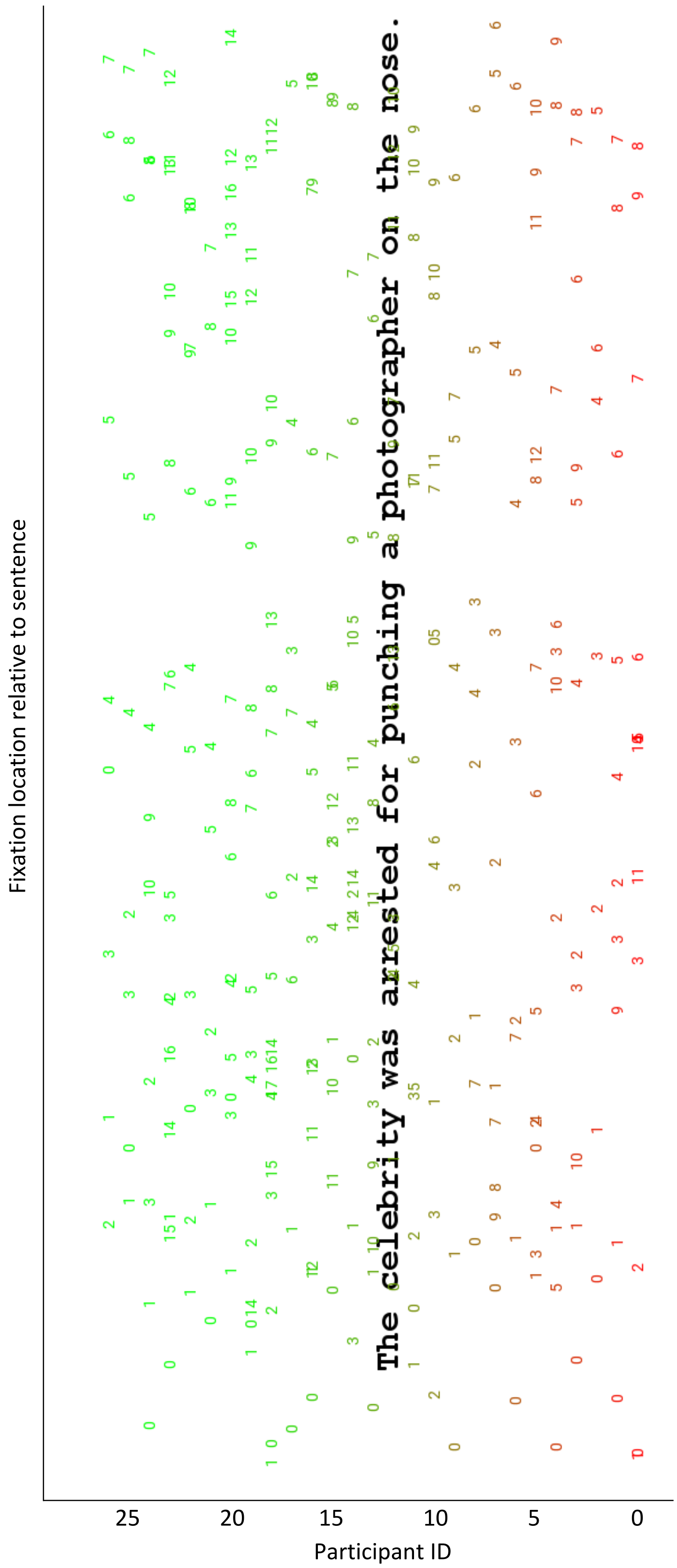

Figure 4.2. Plot in which the locations of the fixations of 27 participants reading the sentence in the figure are plotted along the long axis in line with the sentence. The order of fixation is denoted by the numbers, beginning from zero. Participants are separated along the *y*-axis.

Three parameters were used to define gaze movement during reading: fixation position, fixation duration and saccade duration. There are three main simplifications to this model. The first is that all the eye movements are considered either a fixation or a saccade. Though there does exist smooth pursuit eye movements, used to track a moving object, this type of eye movement is not used to read static text. More fine analysis of eye movements reveals the presence of microsaccades, involuntary saccades during fixation; drifts, slow curved movements between microsaccades; and tremors, very fast small oscillations superimposed on drifts. These are each comparatively small eye movements and were not considered significant compared to fixations and saccades.

The second is to consider only horizontal eye movements. The reason for this is not because fixations are always made along a perfect horizontal axis like the text that is being read, as in fact fixations do frequently occur above or below the line of text. However it has been found that fixations are shortest when placed optimally on the line of text and increase when made above or below the line [37]. It is thus likely that this simplification would make for a more readable text presentation format, and given that the most important movements are horizontal, it was decided to make this simplification.

The third simplification is to define the motion of saccades using three values: The start and end positions and the saccade duration. Thus precise values of eye motion between fixations are ignored, and an idealised saccade (a saccade taking the shortest route) is assumed.

4.3.3 Reverse engineered eye movements

The most direct and personalised way to translate eye movements into text movements is to use the sequence of fixations and saccades of an individual reading a particular sentence. This gives a list of locations along the sentence at which their eyes fixated, the duration at which they fixated there, and the duration of the saccade between each of these locations.

In biomimetic scrolling, a position is designated on the screen (for example using arrows) for the eyes to maintain fixation while the text scrolls through. The sentence is initially positioned such that the first fixation position is between the arrows. Then, after pausing there for the duration of the first fixation, the sentence takes the duration of the first saccade to move to the second fixation position, and so on until the final fixation. Thus fixation position, fixation duration and saccade duration respectively define sentence position, pause duration and step duration.

This algorithm is drawn as a flowchart in Figure 4.3. Figure 4.4 shows three frames of a sentence being scrolled with biomimetic scrolling.

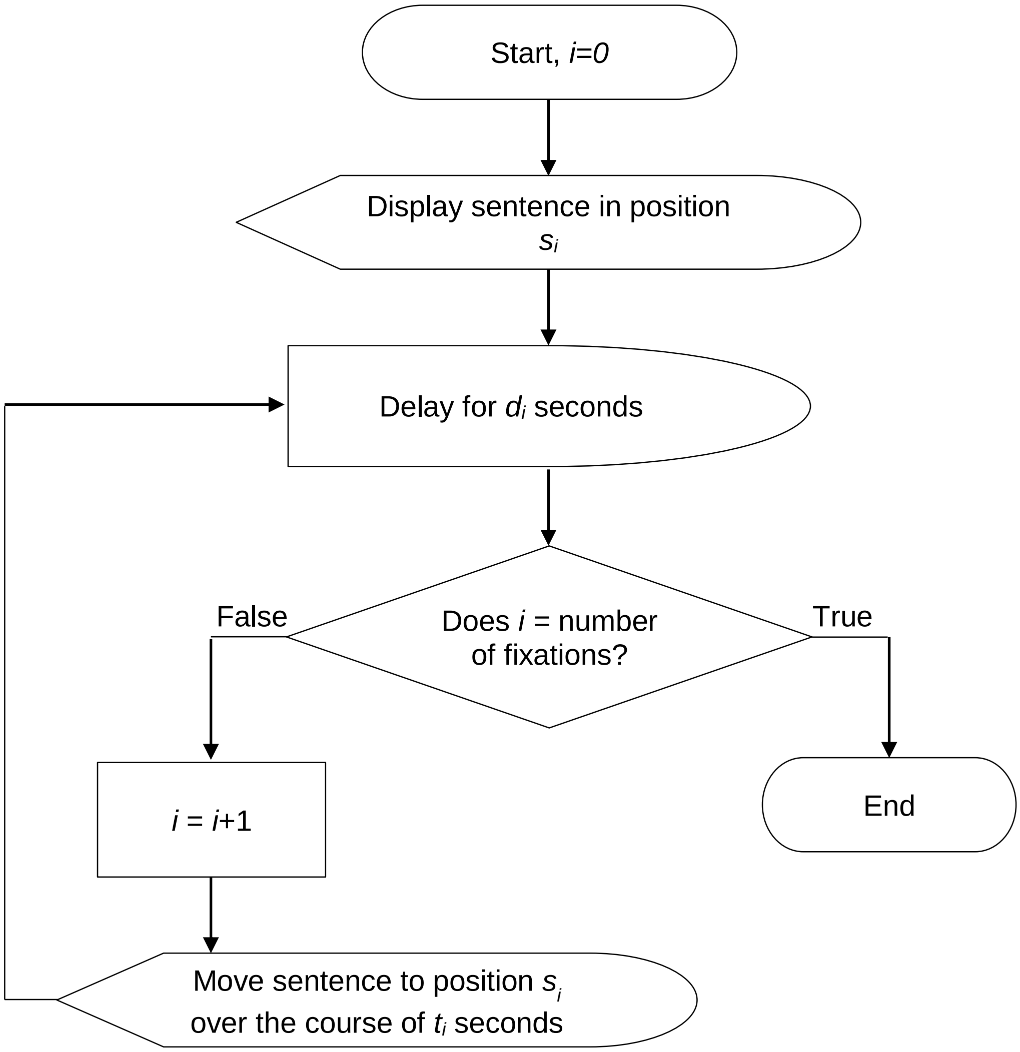

Figure 4.3. Algorithm for biomimetic scrolling according to the data on the eye movements of an individual reading a line of text. s_i is the sentence position corresponding to the i^{th} fixation; d_i is the duration at which the sentence pauses in position; t_i is the i^{th} step duration.

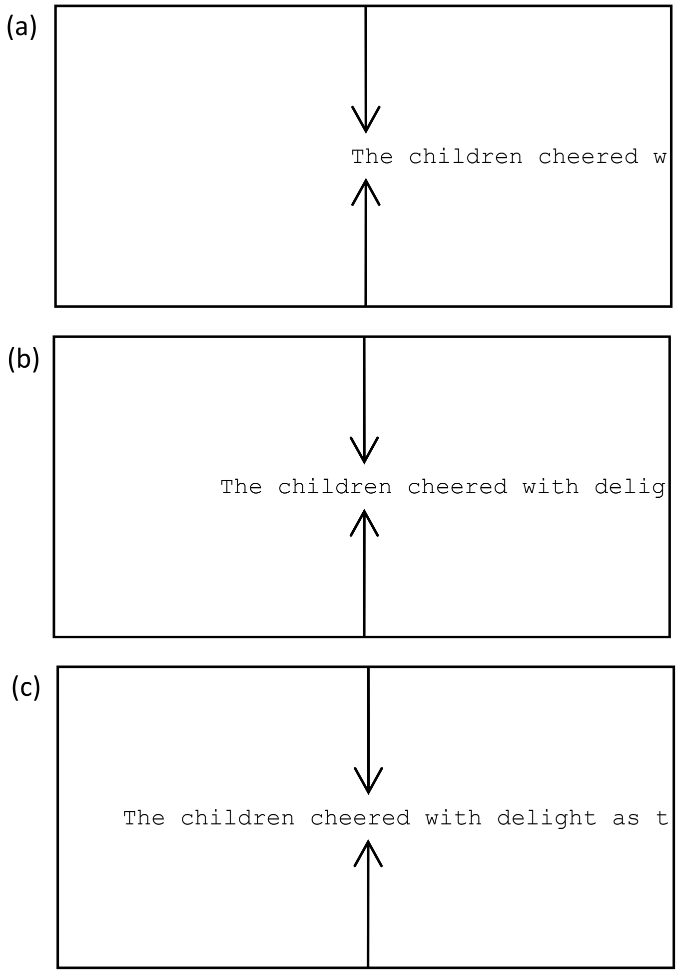

Figure 4.4. An illustration of three frames of the text presentation method, (a) position *i*, (b) position *i+1*, (c) position *i+2*. The rectangular outline illustrates the boundaries of the screen, and the arrows and text illustrate what is displayed on the screen. The function of the arrows is to define the location for the gaze to fixate.

Fixation position, x, needs to be converted into sentence position, s, such that the fixation position is located between the arrows. Each sentence in the eye movement corpus begins with 6 spaces and ends with a full stop, and each character has the same width due to the use of a monospaced font. Fixations positions are given in pixels of the eye tracker where $x=9$ is one character from the start of the sentence. How this relates to pixels of the window displaying the sentence is dependent on the font size, F, according to equation 4.1.

$$s = s_0 - \frac{1}{15}Fx \qquad (4.1)$$

s_0 is the initial position from which point the sentence moves to the left when reading left-to-right. There is a linear relationship between font size and the width of characters, where character width equals 3 fifths of font size. Dividing this by 9 (where x/9 is the number of characters), we arrive at the factor of one fifteenth in equation 4.1.

The fixation duration equals the pause duration, *d*, and the saccade duration equals the step duration, *t*. The motion of the step mimics the motion of an idealised saccade [38]. This was implemented with the *in_out_expo* transition function of the Animation object in the Kivy library, which approximates a Gaussian. Speed of scrolling is implemented using a multiplicative factor to moderate pause and saccade duration.

4.4 Parameters of biomimetic scrolling

4.4.1 Introduction

The chain of fixations and saccades is different for different individuals, resulting in subject-specific text movements. There are, however, trends in the data. This section considers these trends and how they inform the choice of parameters for biomimetic scrolling. There are many viable combinations of these parameters, which may suit various contexts. Here we choose a particular set for testing.

4.4.2 Pause duration

One parameter of biomimetic scrolling is the pause duration of the text as it passes between the arrows - equivalent to fixation duration in normal reading. We chose to set the pause duration equal to the total viewing duration, the sum of all fixation durations on a word. The total viewing duration was averaged over all participants in the eye movement corpus for each word of each sentence. This was possible because the sentences used in our reading speed study were the same as those used in the eye movement corpus.

We now propose a method to allow us to extrapolate to sentences for which eye movement data has not previously been measured. A well-established finding is that a reader's gaze dwells longer upon low-frequency (less common) words than on high-frequency words [39]. The experiment data plotted in Figure 4.5 confirms this finding. Word frequencies are expressed on the logarithmic Zipf scale, which equals the logarithm to base 10 of frequency-per-billion-words. It ranges from around 1 for the lowest frequency words to around 7 for the highest [40]. The word frequency is correlated with the total viewing duration with a correlation coefficient, r = -0.81. A line of best fit was calculated using the method of least squares, giving a gradient of -61±1 ms/Zipf and intercept of 567±6 ms. This linear relation provides a way to estimate the total viewing duration, and hence a suitable pause duration, from the word frequency.

There is also a correlation between total viewing duration and word length (r = 0.84), as shown in Figure 4.6. The line of best fit was calculated using the method of least squares, giving a gradient of 37 ± 1 ms/letter and an intercept of 45 ± 3 ms. This gives a second way to estimate total viewing duration and hence to choose an appropriate pause duration, based on word length. As word length and frequency are correlated [41] only one of these measures is needed to set pause duration.

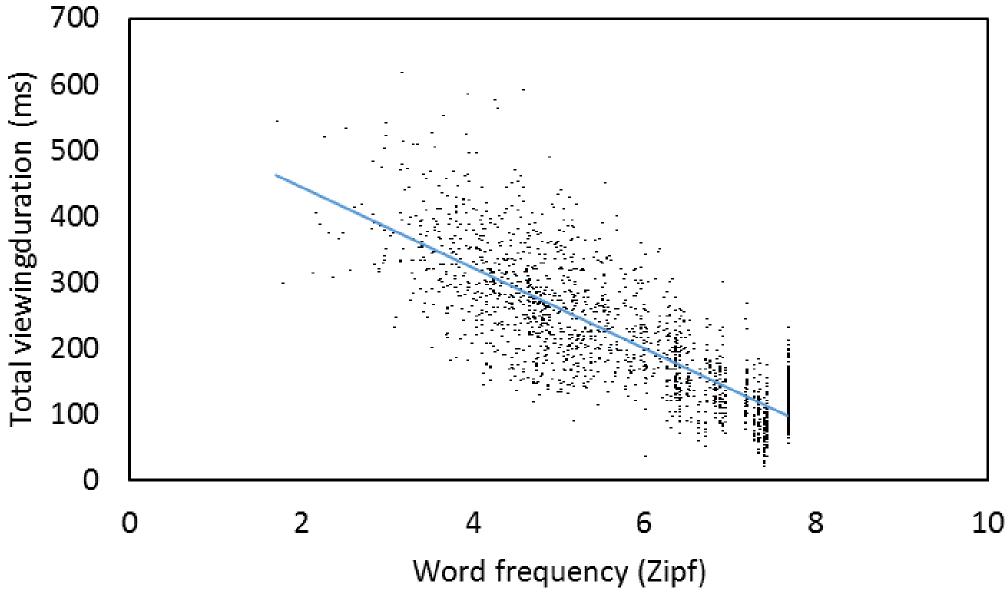

Figure 4.5. Plot of total viewing duration against word, averaged over the 67 participants of the eye movement corpus.[a]

Figure 4.6. Plot of total viewing duration against word length, averaged over the 67 participants of the eye movement corpus.[a]

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[a] Words included in multiple sentences are included here multiple times with the same Zipf but not necessarily identical reading times.

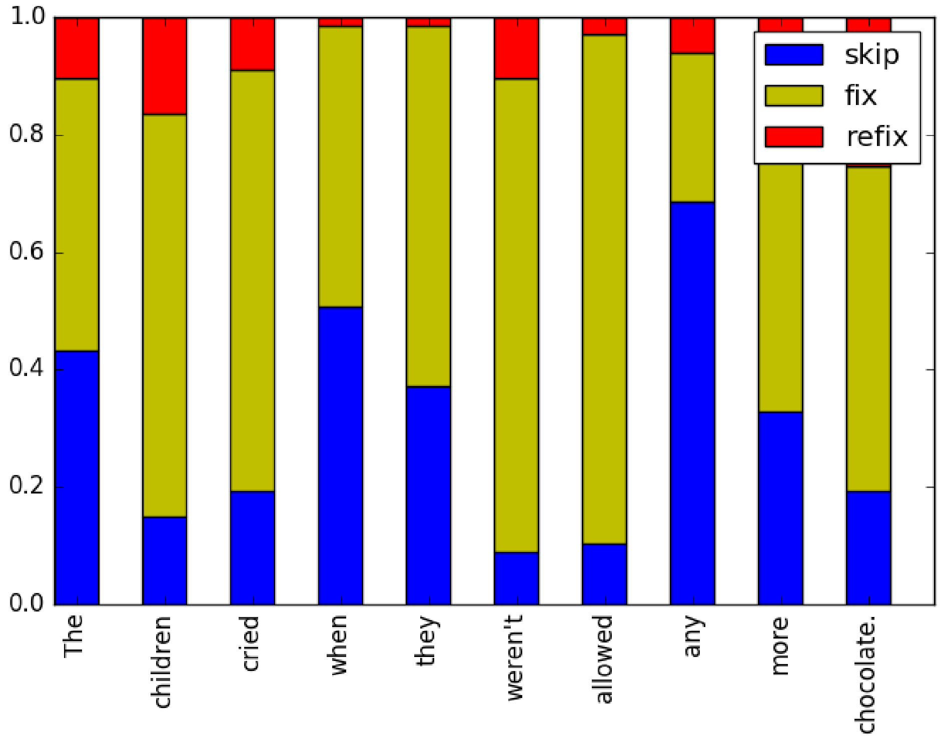
4.4.3 Number of pauses per word

In normal reading, not every word is fixated. Thus one parameter that can be adjusted is the number of pauses per word. This may be zero, equivalent to a skipped word, one, equivalent to a fixated word, or two, equivalent to a refixated word. Using more pauses is, of course, possible, but is likely only to be need for low vision users reading highly magnified text.

Using the eye movement corpus, skipping probability, p_0, fixation probability, p_1, and refixation probability, p_2, were calculated for each word of each sentence. These probabilities were calculated as the average number of skips, fixations or refixations, where in each case, p_0, p_1 and p_2 sum to unity. First pass reading was used, in other words, the first encounter with a word.

Figure 4.7 shows the skipping, fixation and refixation probabilities for each word from two of the sentences of the eye movement corpus. This illustrates the known effect that short, common words tend to have higher skipping probabilities. In the second sentence, for example, the word ‘a’ was barely looked at, whereas the words ‘photographer’ and ‘punching’ almost always were. Given this is an organic system, there is natural variation from sentence to sentence, as illustrated by the word ‘the’ which features in both sentences. In both cases, the word has a relatively high skipping probability but the actual value of p_0 is not the same.

(a)



(b)

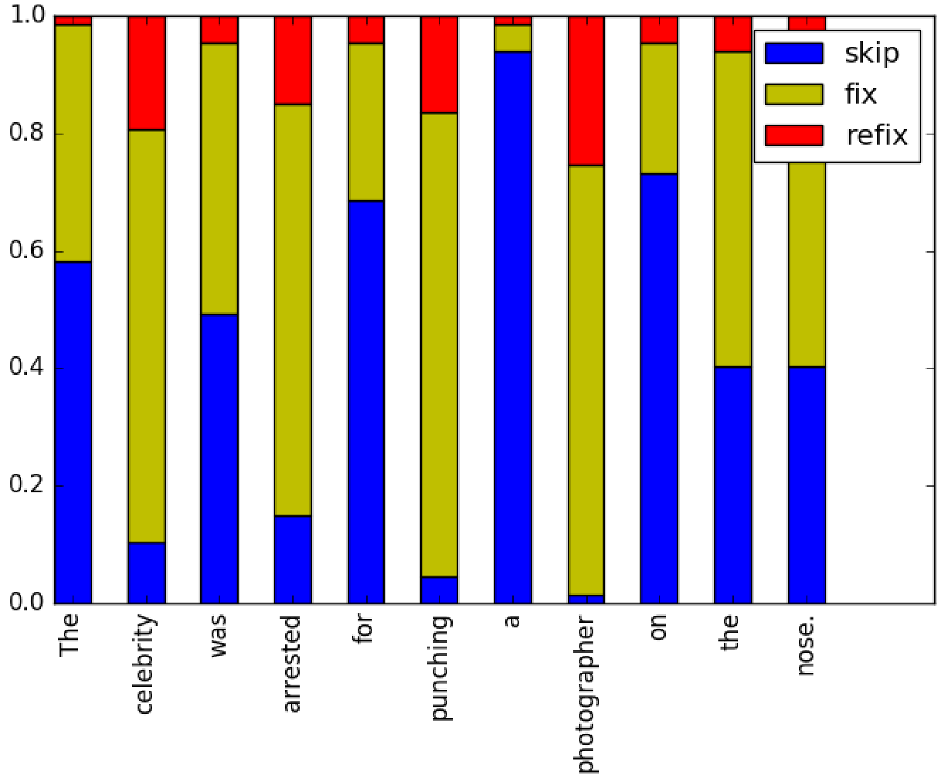


Figure 4.7. Skipping probability, fixation probability and refixation probabilities for each word of two sentences using data from all 67 participants of the eye movement corpus. (a) Sentence 1, (b) Sentence 2.

The number of fixations and the total viewing duration are highly correlated (*r* = 0.97), as shown in Figure 4.8. Therefore, only one of the two parameters, number of pauses and pause duration, needs to be varied with word. Using pause duration allows for more precise control than number of pauses, as duration is a continuous scale whereas the number of pauses generally only varies between values of zero, one and two. In addition, most words can be seen within a single fixation as the typical visual span is around 10 characters [42]. Thus we chose to set a pause count at a constant of 1 per word and to vary pause duration.

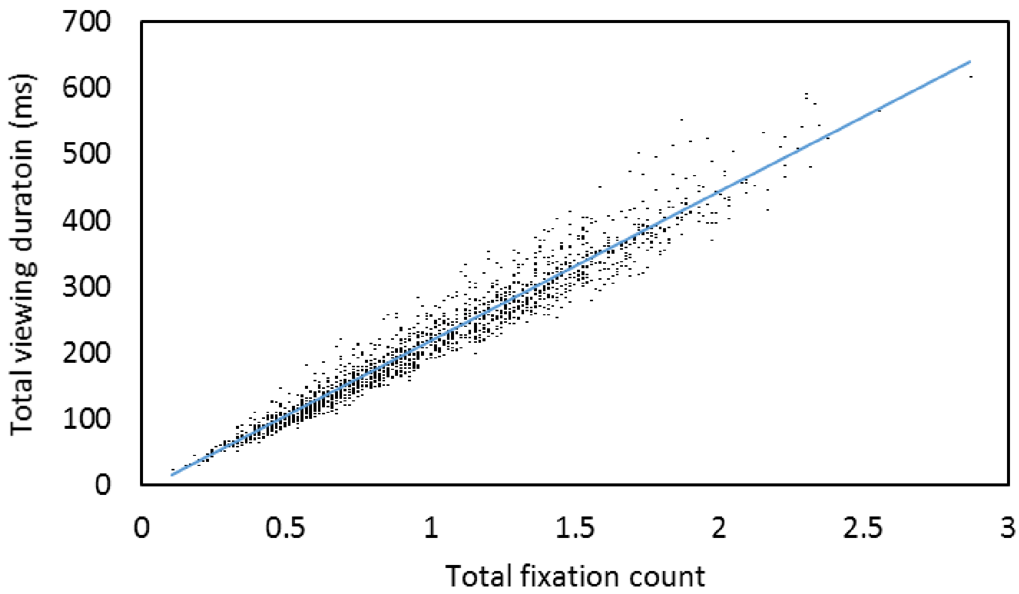


Figure 4.8. Plot of the total viewing duration as a function of total fixation count, averaged across all 67 participants in the eye movement corpus.

4.4.4 Viewing position

Another parameter is the viewing position of the word that is fixated, the position of the word between the arrows. The optimal viewing position (OVP; the position where readers *should* fixate) is not identical to the preferred viewing location (PVL; the location where readers *do* fixate) [43]. Findings from single-word and text reading studies suggest that word centre is the optimal position for word processing [37]. The preferred viewing location, on the other hand, is slightly left of word centre [44]. Both the OVP and PVL are affected by word length [43]. For the reading study, we chose to set the viewing position as the centre of the word instead of choosing it according to data from the eye movement corpus.

4.4.5 Step duration

Step duration is another parameter that can be adjusted. The mean saccade duration of the eye movement corpus is 36 ms. This is so short in comparison to typical fixation durations that we feel justified in setting the step duration to zero, meaning instantaneous movement between pauses.

4.4.6 Speed

The pause duration and step duration together set the speed with which the text scrolls. As scrolling speed is usually the parameter over which the user would have control, we set it as a multiplicative factor to proportionally modulate pause duration. Thus a change in the speed setting, measured in words per minute (wpm), proportionally increases or decreases the pause duration of each word.

4.5 Reading speed study

4.5.1 Introduction

We hypothesize that biomimetic scrolling will enable users with normal vision to read at a faster rate than continuous scrolling as it is more similar to natural eye movements. As biomimetic scrolling and RSVP both remove the need for eye movements, we expect reading speeds using them to be similar. In order to test this, we carried out a study with 30 normally-sighted participants (different to those from the eye movement corpus), aged between 19 and 62, with a split of 16 males and 14 females.

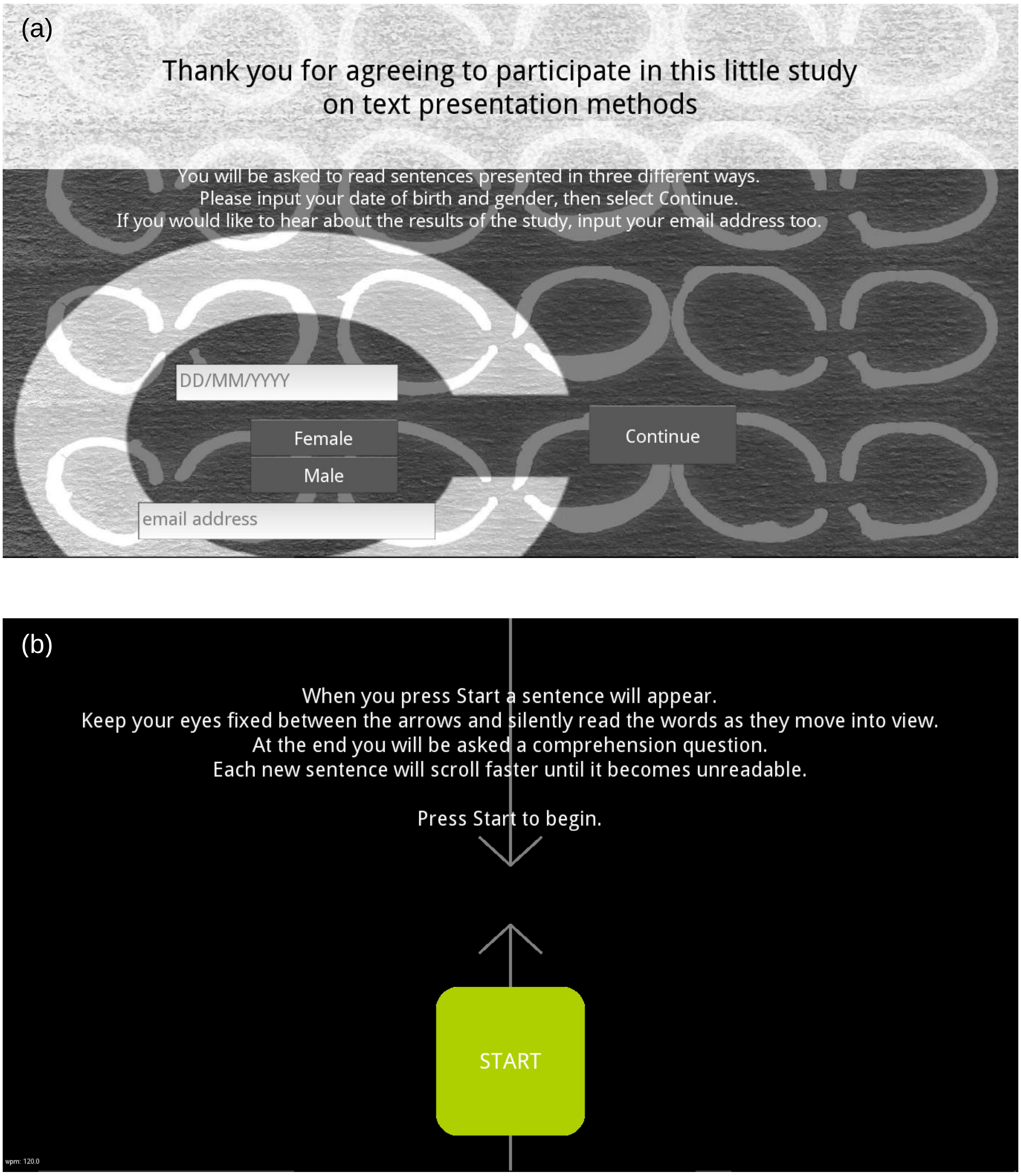
4.5.2 Method

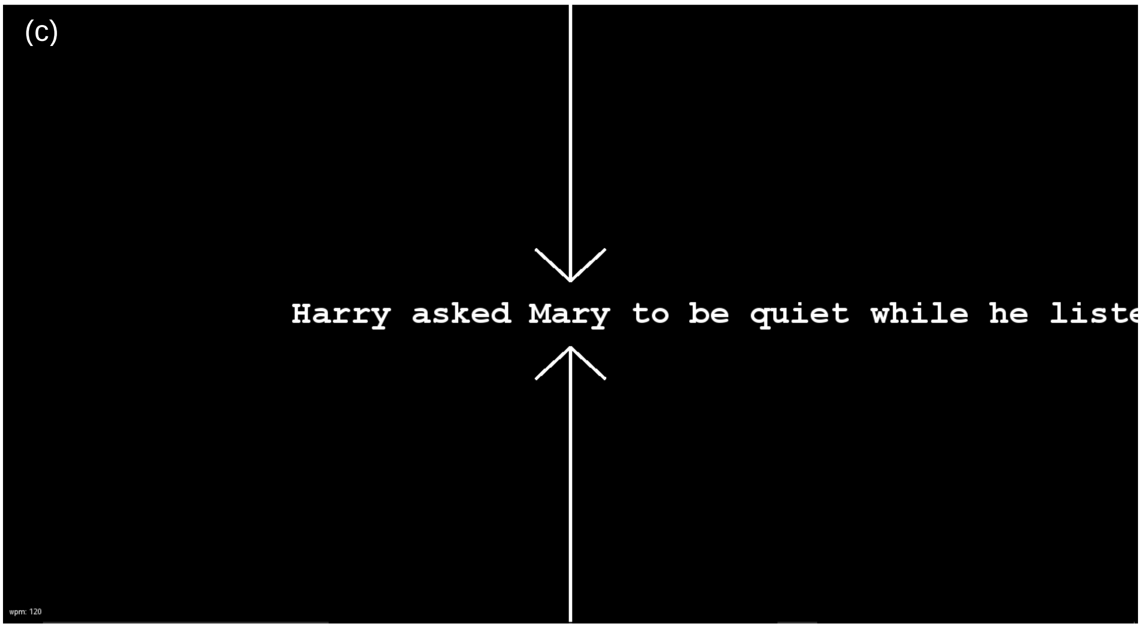
Three text presentation methods were used: Continuous scrolling, in which a line of text entered from the right of the screen and smoothly scrolled across the centre until it disappeared off the left side; RSVP, in which words were displayed one at a time with equal duration in the centre of the screen; and biomimetic scrolling, with a pause duration equal to the average total viewing duration from the eye movement corpus. In the case of biomimetic scrolling, the participants were instructed to keep their eyes fixed between the arrows and read the words as they came into view.

The sentences were selected from those used in the eye movement corpus. Those that were between 12 and 14 words long and with a total number of characters between 68 and 76 were chosen. 40pt, Courier New font (a monospaced font), with white letters on a black background, was viewed from about 50 cm on an LCD screen with horizontal width of 34 cm and brightness of 210 cd/m^2 for white.

The order of presentation methods was randomized. Each method was set to begin at a speed of 120 wpm. At the end of each sentence a multiple choice comprehension question was asked, with three choices plus a fourth option to indicate when they did not know the correct answer. The same speed level was used twice, then increased to the next level, with each level separated by 120 wpm. The testing would end when they select “I don’t know” four times in a row, or when it reaches 1920 wpm for biomimetic scrolling and RSVP or 600 wpm for continuous scrolling. These ceiling levels were high enough not to constrain any participants. The maximum reading speed was taken as the maximum speed level at which both questions were correctly answered.

An app was created in Python to implement the text presentation strategies, to create the graphical user interface and to record the data. Figure 4.9 shows the graphical user interface of the app at various points in the testing procedure. Participant date of birth and gender is taken on the welcome screen, Figure 4.9(a), with an optional email entry space for receiving news of the results. Before each new text presentation method, instructions are given as shown in Figure 4.9(b), and a start button is pressed to begin sentence presentation. After each sentence display, Figure 4.9(c), a multiple choice question is given as displayed in Figure 4.9(d). After selection, the start button returns for the participant to begin the next sentence presentation. At the end, a closing screen thanks the participants for their participation.


(a)
Thank you for agreeing to participate in this little study
on text presentation methods
You will be asked to read sentences presented in three different ways.
Please input your date of birth and gender, then select Continue.
If you would like to hear about the results of the study, input your email address too.
DD/MM/YYYY
Female
Male
Continue
email address
(b)
When you press Start a sentence will appear.
Keep your eyes fixed between the arrows and silently read the words as they move into view.
At the end you will be asked a comprehension question.
Each new sentence will scroll faster until it becomes unreadable.
Press Start to begin.
START



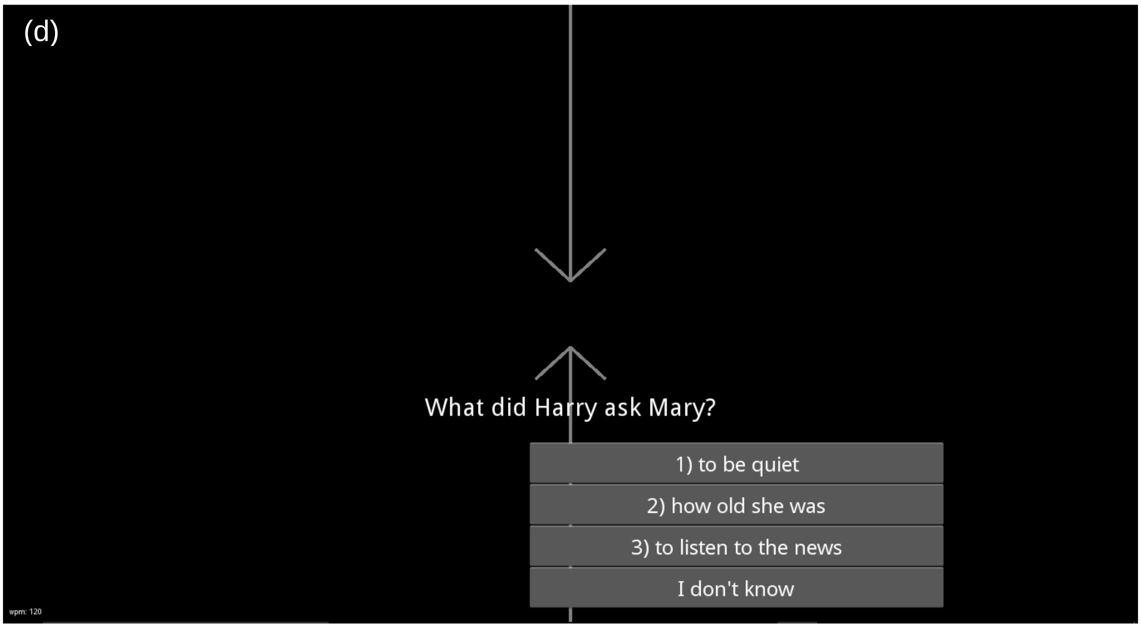


Figure 4.9. Graphical user interface of the reading speed testing app. (a) Welcome screen, participant details input; (b) Instructions screen and start button; (c) Sentence display screen; (d) Multiple choice question screen.

4.5.3 Results

All 30 participants achieved a higher reading speed using biomimetic scrolling than continuous scrolling. Comparing with RSVP, 13 read faster with biomimetic scrolling, 14 with RSVP and 3 achieved equal speeds. Figure 4.10 shows the reading speed averaged over all the participants for each presentation method. The results suggest that biomimetic scrolling is almost 5 times faster than continuous scrolling, whereas reading speed appears to be similar for biomimetic scrolling and RSVP.

For statistical evaluation, data were analysed with a linear mixed-effects model (LMEM) with by-subject random intercepts, using the *lmer* program of the *lme4* package for R [45]. To evaluate the effect of presentation method on reading speed (wpm), we used treatment contrasts in which the biomimetic scrolling condition served as the reference group. Consequently, the intercept for the fixed effect presentation method estimates the mean value for the biomimetic scrolling condition. The two slopes estimate the difference between continuous scrolling and biomimetic scrolling and between RSVP and biomimetic scrolling. For the LMEM we report regression coefficients (b), standard errors (SE) and t-values ($t = b/SE$). A two-tailed criterion ($|t| > 1.96$) was used to determine significance. In the LMEM, the estimated reading speed for biomimetic scrolling was 952 wpm (SE = 60.4, t = 15.62). For continuous scrolling, reading speed was significantly slower (b = -748, SE = 78.7, t = -9.50); specifically, mean reading speed was down to 204 wpm. When reading with the RSVP method, mean reading speed did not differ significantly from the biomimetic scrolling condition (b = 52, SE = 78.7, t = 0.66).

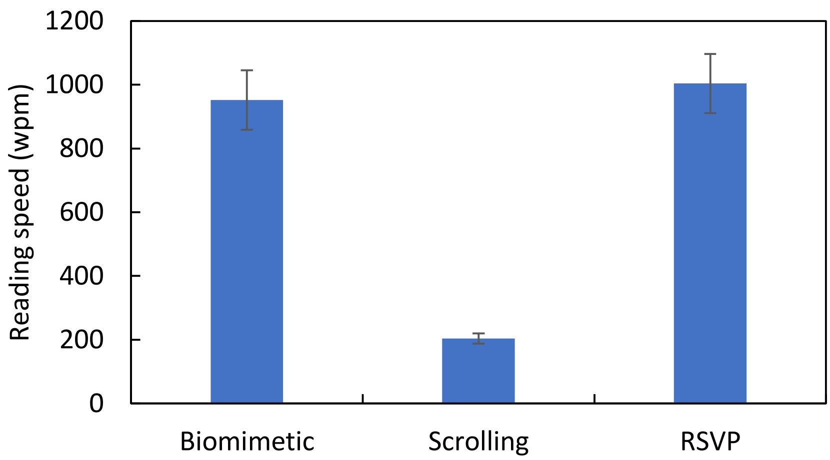


Figure 4.10. The mean reading speed for all participants, with the error bars indicating standard error on the mean.

4.6 Discussion

Biomimetic scrolling is a smart form of line-stepping text presentation in which the sentence moves in a sequence of saccades and pauses with respect to a fixation point on the screen. The choice of length and duration of these saccades and pauses is made with reference to eye movement data in order to mimic normal reading. Like RSVP, biomimetic scrolling saves time by removing the need for eye movements. This speeds up reading both by removing the time needed to make the saccade and the time needed to program it, typically approximately 180 to 250 ms [46].

Using an algorithm to define the saccades on behalf of the reader imposes on them an average, ignoring differences in eye movement behaviour among individuals [47]. These differences were in evidence with equal numbers of participants achieving a higher reading speed with biomimetic scrolling and RSVP. This suggests that text presentation does not admit a one-size-fits-all approach and having additional methods can benefit more people. There is scope for further research on tailoring biomimetic scrolling to individuals by using that individual's eye movement data rather than an average.

For this technique to be used for reading outside of an experimental setup, control would need to be given to the reader. Speed control is the most obvious, and has already been discussed. Tailoring the other parameters of biomimetic scrolling, such as pause duration and viewing position, is also possible. Regressions are an important part of reading which cannot be imposed on the reader and their absence in RSVP has limited its success [20,21]. Thus user control is a key topic for further research.

No practice was given to participants before starting the trial. With RSVP, the gaze automatically remains on the single word at the centre of the screen. But with biomimetic scrolling, as words are still present to either side of the centre, participants have a choice whether to keep their eyes steady or move them with the words. For this reason, giving the participants no practice may have adversely affected performance on biomimetic scrolling more than RSVP. A previous study has shown that practice in RSVP reading improves reading speed, perhaps due to the plasticity of the visual system [48]. Further work is required to investigate the effect of practice on reading speed and to monitor eye movements while biomimetic scrolling text.

Reading speed is just one measure of the success of a text presentation method. Subjective measures of user comfort and satisfaction are also needed to determine the comparative potential of this technique. In addition, only a basic level of comprehension was tested after reading a single sentence. The effectiveness of biomimetic scrolling under sustained reading conditions and its effect on comprehension compared to normal reading is yet to be determined.

In biomimetic scrolling, readers view the text with movements characteristic of natural reading, but without choosing the movements. The psychology of reading using biomimetic scrolling would need further investigation to understand how it differs from other reading formats. Specifically, by using eye tracking, the movement of the eyes whilst reading can be monitored to determine whether participants are sticking to the suggestion of maintaining a steady gaze at the fixation point.

RSVP was introduced by Forster in 1970 as a method to study reading [49] before its potential to hasten reading was looked at [50,51]. Conversely, biomimetic scrolling has started life as a tool for reading, but may be of use to psychologists to better understand one or other aspect of reading. Indeed, as particular parameters of reading can be imposed upon a reader with great precision, the response of the reader can be measured.

4.7 Conclusion

We have described a novel method, biomimetic scrolling, for scrolling text that enables reading at almost 5 times the rate of continuous scrolling. It directly incorporates knowledge about reading generated through decades of research and provides a comparable alternative to RSVP as a speed reading technique.

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CHAPTER 5

Smart glasses and dynamic text presentation as a novel reading aid for age-related macular degeneration

5.1 Introduction

In Chapter 3, it was reported that the majority of those with AMD were able to see the majority of the smart glasses screen, despite the Epson Moverio BT-200 display being positioned in the centre of the visual field. It was found that the display conferred an inherent benefit on word recognition, with participants achieving a better logRAD score reading from the smart glasses than from paper. In addition, 70% subjectively found it easier or equally easy to read from the smart glasses than from paper.

However, the average reading speed whilst reading from the smart glasses was slower than from paper. The text was presented in the regular page format in order to act as a direct comparison to the printed text. It was noted, however, that this does not make optimal use of the display and that further work would need to be done to achieve this.

Chapter 4 describes the development of a novel strategy for presenting text that is derived from the natural movements of the eye whilst reading. It was conceived to work in conjunction with the steady-eye strategy, which those with macular disease are recommended to practice. Biomimetic scrolling then facilitates reading with the natural characteristics, the way individuals habitually read prior to developing a visual impairment.

This chapter maintains this line of research by trialling biomimetic scrolling on subjects with AMD, and comparing it to other forms of text presentation. The text is presented on the smart glasses that were previously piloted and compares the reading performance achieved by each individual on this device to the performance achieved with their habitual optical aid.

From an individual patient perspective, the reading strategy that offers that person the best results is more important than the average results of a sample population with macular disease. Within such a sample a large range of reading deficits are present, ranging from almost an inability to read, to a slight disadvantage over the normally sighted. The ability to customise the content presentation has been found key to improving the visual experience for a range of visual abilities [1]. In addition to the differences in visual ability are the differences in verbal skills, an increasingly prominent factor in the literature on reading [2]. The versatility of electronic displays allows each individual to be presented with text in a manner precisely according to their specific needs. The aim of this chapter, then, is not to find the manner of text presentation with the highest average across a sample. Rather, it is to find a number of text characteristics each of which is found beneficial to some proportion of the sample, be it just one individual. With the text presentation method best tailored to each individual, a comparison is then made to the habitually used optical magnifier.

The methodology of the patient study is first outlined, followed by a description of the software used in the study which enabled the smart glasses to be used as a reading aid. The results of the study are then presented in the subsequent sections. The principle results concern the text presentation strategies and how these, in conjunction with the smart glasses, compare to the reading aid habitually used by the participants. Results are also presented for the use of jitter, the independent control of each display and how participants compare the smart glasses to a laptop display. Together, the sections of this chapter outline the workings of a customisable, head-mounted, low vision reading aid.

5.2 Design of experiment

5.2.1 Participants

Participants were recruited from the low vision clinic of Princess Alexandra Eye Pavilion, Edinburgh, UK and from the Macular Society. 23 participants were recruited for this study, 17 female and 6 male, with an average age of 81 (SD 7, range 60 to 91). Participant data is compiled in Table 5.1.

Table 5.1. Participant summary data on clinical characteristics and past experience.

ID	Sex	Age	Reading acuity (logMAR)	AMD details	Years since diagnosis	Registration status	Experience of electronic LVAs?	EV training?
111	M	91	1	Dry both	6	Not registered	Y	N
112	F	91	1.6	Dry both	23	Blind	N	Y
113	F	86	0.7	Wet both	<1	Not registered	N	N
114	F	74	1.2	Wet both	<1	Not registered	N	N
115	F	78	0.6	Macular hole in both eyes	4	Not registered	N	N
116	F	83	0.8	Dry in both	8	Partially sighted	N	N
117	F	80	>1.7	Dry both	13	Blind	Y	N
118	F	89	1.2	Dry	3	Blind	N	N
119	M	88	0.6	Dry R, Wet L	5	Not registered	N	N
120	F	79	>1.7	Juvenile, Dry both	62	Blind	Y	N

121	M	82	0.8	Dry both	6	Partially sighted	N	N
122	M	79	1.1	Dry both	20	Not registered	Y	N
123	F	82	0.75	Wet L, R perfect	20	Not registered	N	N
124	F	81	0.5	Dry and wet	7	Not registered	N	Y
125	F	84	1.5	Dry	15	Blind	Y	N
126	F	86	1.1	Dry both	2	Partially sighted	Y	N
127	M	60	1.3	Dry both	4	Partially sighted	Y	N
128	F	83	1.05	Macular dystrophy	1	Partially sighted	N	N
129	M	89	>1.7	Wet R, blind L	12	Partially sighted	N	N
130	F	87	1.2	Dry both	3	Partially sighted	N	N
131	F	75	1.5	Dry in both, wet in R	13	Blind	Y	Y
132	F	69	0.9	Dry both	15	Partially sighted	Y	Y
133	F	74	1.5	Dry in both, wet in L	5	Not registered	N	N

5.2.2 Ethical approval

An amendment to the earlier patient trial was submitted and gained favourable opinion from the Leicester South NHS Research Ethics Committee, and R&D approval from NHS

Lothian. The amendment included details about procedure, sample size and recruitment. These were updated in the protocol and participant information sheet. Heriot-Watt University continued to act as the sponsor and to cover insurance and indemnity.

5.2.3 Procedure

After informed consent was given by the participant, the following steps were taken:

1. Reading acuity and maximum reading speed were measured using the Radner Reading Chart. Participants held the chart at a comfortable angle, but at a distance of 25cm. Those who could not read the top line from this distance were allowed to hold it at a comfortable distance, with the distance measured and taken into account for the measurement of reading acuity. Subjects were instructed to read the sentences aloud as quickly and accurately as possible, and to read to the end of the sentence without correcting any errors. The time from start to finish of each sentence was measured with a stopwatch. Subjects continued reading the sentences down the chart until it was too small for them to read.
2. Oral reading speed was measured using the optical magnifier habitually used by the participants, in the manner described in section 5.4.4.
3. The smart glasses were presented to the participant and its functioning explained. Sample text was presented on the display in their critical print size. The size was adjusted based on their preference.
4. Three colour options were shown to the participant: Black text on a white background, white on black and black on yellow. Their preferred choice was used for the duration of the study.
5. The maximum reading speed using the four dynamic text presentation options, biomimetic scrolling, continuous scrolling, RSVP and static, were measured in a randomised order according to section 5.4.4.
6. Sample text with and without jitter was shown to the participant for them to indicate their preference, according to section 5.5.
7. Sample text was shown in the left, right and both screens for the participant to indicate their preference, according to section 5.6.
8. A questionnaire was asked to the participants about their experience of using the smart glasses, according to section 5.4.6.

9. Sample text was shown on the laptop and participants were asked to compare the laptop screen to the smart glasses in terms of which they could see better.

5.3 Text presentation app

5.3.1 Functioning and graphical user interface

The software used for tailoring and displaying dynamic text was written in the Python programming language, with particular use of the Kivy library for the graphical user interface. Included are the screen visibility tests described in Chapter 3, the settings screen, the camera text input screen and the text presentation screen.

In the study, the patients only see the text presentation screen. This screen is kept clean and simple, displaying only the text and vertical lines above and below the point of fixation. The operation of the programme was made by the investigator in order to minimise strain on participants.

The settings screen, Figure 5.1, was implemented using the Settings module of the Kivy library. Three panels are used within the settings screen: Settings related to the presentation of text, displayed in Figure 5.1; settings related to the screen visibility tests; and the default Kivy panel, which contains the settings related to the functioning of the application itself, such as full screen, input processing and mouse visibility. A JSON definition file contains the text display and screen visibility settings, including default options, a description and the widget used for input (such as Boolean, drop-down menu or numeric input). The settings screen can be accessed at any time, and a change in one of the settings fires an event which leads to the text being immediately updated. Once input, the settings are saved and automatically loaded the next time the app is loaded.

The extent of visibility of test, described in Chapter 3, is included to map out the areas of the screen visible and invisible to the user. Upon conclusion of the test, the results are presented to the user, showing the points they did and did not see. The user then selects the area of best visibility relative to the central fixation point; this estimates their preferred retinal locus (PRL). On the text presentation screen, a fixation target (a cross) is displayed such that focussing the central vision on the cross positions the text in the PRL. A screen with a circle of numbers resembling a clock face is also included as an alternative test of the PRL: By focussing at the centre of the circle, participants describe the numbers that are clearest.

In the main study, a fixation target was not used. However, this was presented to two patients. It was found that the extent of visibility test and the clock face test agreed in their estimation of the PRL in both cases. However, the use of the fixation target whilst reading was not easy for the participants. The first had no knowledge or experience of eccentric viewing and required more training in order to make use of this strategy. The second was very experienced at eccentric viewing and thus had their own way of doing it, without the use of a fixation target.

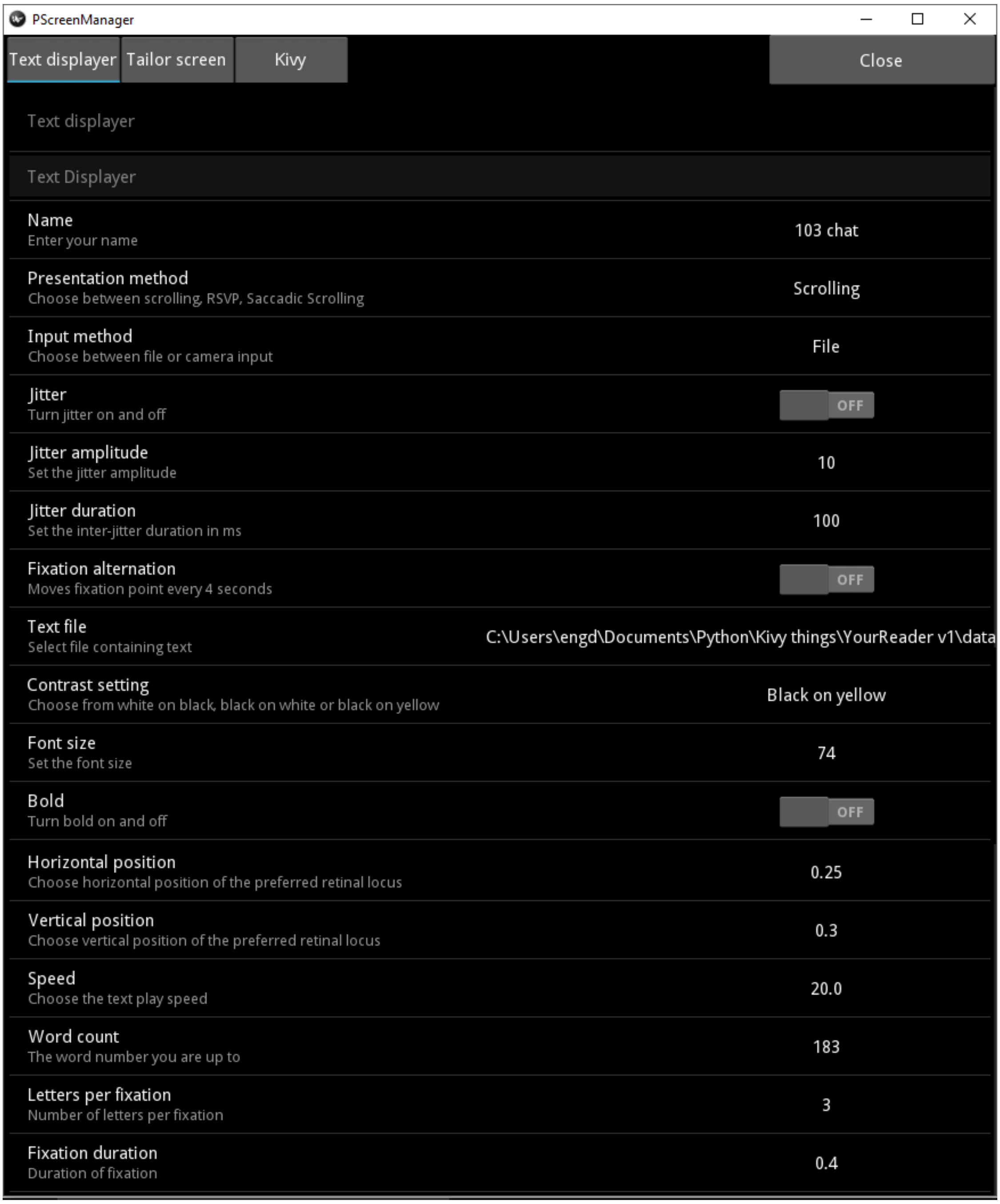

Figure 5.1. The settings screen of the text displayer software, with the text displayer panel showing.

5.3.2 Text control

In the patient study, the text was scrolled across the screen at a speed pre-determined by the experimenter. In a real world setting, however, the user would control the dynamics of the text themselves. Mention will be made here of the controls in the app that enable the user to do this, though it was not a part of the study.

Two modes of control were implemented: Automatic and manual. In automatic mode, the speed is set and then the start button pressed to begin the scrolling. Once scrolling, the speed can be increased or decreased and this change is instantaneously implemented. In manual mode, users can move forwards or backwards across the text through use of left and right buttons. Upon single presses of these buttons the text moves across a few letters with a steadily decaying velocity profile. If the button is held down, the text scrolls at the user-set speed until the button is released.

If using a keyboard, the up and down arrow keys control the speed, left and right buttons for manually moving forwards and backwards across the text, and the enter button to start and stop automatic scrolling. A Bluetooth controller made by Homido, Figure 5.2, was also programmed for use by the app. The joystick, controlled by the thumb, can be moved in four directions and makes for a natural feel for controlling the text.

Figure 5.2. Bluetooth controller made by Homido [Image credit: http://www.homido.com/en/shop/products/gamepad-bluetooth]

5.3.3 Text input

The text presentation software is ideally suited to digital text input, which it then manipulates in order to display text in the optimal format for the user. Text files were used for inputting the text used for the trials. This could easily be extended to other file formats that admit text extraction. Text extraction from websites could also be implemented. In all these cases, the data is already in text format and needs only to be transferred to the software.

In order to widen the scope of potential applications for the software, inputting non-digital textual information would also be needed. Indeed, one trial participant could visualise using the smart glasses to read the dials on his cooker, labels on packets and the bus numbers of approaching buses. In order to optimise the textual display of such information in the manner described in this chapter, and method for converting this optical information into digital text is required. Optical Character Recognition (OCR) is the term given to this task.

Smart glasses have built-in cameras and are thus already equipped for optical input. The Epson Moverio BT-200 includes a VGA camera with 0.3 megapixels. This is somewhat mismatched with its QHD display meaning that the direct video feed from the camera is at a lower resolution than the display. This is improved in the Moverio BT-300 which includes a 5 megapixel camera.

Basic OCR capability was included in the app through the use of the Tesseract OCR engine. Originally developed by Hewlett-Packard, the Tesseract engine is now open source and developed by Google. In the app, an image is captured through use of the Kivy camera widget and previewed to the user. Upon the user's acceptance, the image is passed on to the Tesseract engine for processing. The text that is output is then displayed according to the settings suited to the user. This function currently only works in very restrictive settings, with the text needing to be of sufficient size, orientation and contrast. Further development would be needed in order for this to be used in real world settings.

A final option for text input is to simply use the smart glasses as a CCTV, displaying the live video feed from the camera onto the display. This does not allow the kind of control over the presentation of text which has been utilised in this chapter. Nevertheless, through some of the image processing techniques already reviewed [3], the image can be enhanced.

5.4 Text presentation

5.4.1 Introduction

Section 4.1.3 provided a short review of the principal methods of text presentation. The subsequent subsection, 4.1.4, then outlined the research conducted on the use of text presentation to benefit reading with visually impairment. The two principle methods considered were rapid serial visual presentation (RSVP) and horizontally scrolled text (also referred to as leading or times square presentation). Some evidence was found for that these dynamic methods of text presentation could increase reading speed over use of static text.

The introductory section of Chapter 4 ended with the question that motivated the creation of biomimetic or saccadic scrolling: If text was presented in a way that mimicked natural eye movements whilst reading, in the way patients read before acquiring their visual impairment, could reading be enhanced? The principal focus of Chapter 4, however, was the development of the novel text presentation method that would produce this effect. It was tested on the normally sighted and found to match the speed of RSVP and increase the speed of scrolling text by a factor of approximately five.

One of the aims of this chapter is to investigate these dynamic methods of text presentation on those with macular disease. Thus, RSVP, scrolling and biomimetic scrolling are compared to static text. The primary outcome measure is reading speed. In addition, the subjective preference of participants is considered.

Through testing these methods, and adjusting the size and colour contrast of the text to the participant's preference, the text is then individually tailored. This tailored text, presented on the digital display on the smart glasses, is next compared to reading with the participant's habitual optical aid. Just 9 out of 23 participants (39%) have had experience using electronic low vision aids, and even fewer use them habitually. However, all participants have used optical low vision aids, and most use them habitually. In addition, optical low vision aids, usually a magnifier of strength appropriate to their eyesight with a built-in light, are frequently provided by the low vision clinic at the Princess Alexandra Eye Pavilion, Edinburgh. Thus, it was decided to compare the smart glasses tailored text display to the participants' habitual optical aid.

5.4.2 *Biomimetic scrolling settings*

The fourth section of Chapter 4 outlined the parameters of biomimetic scrolling and described how these parameters were set for the study involving normally sighted participants. Different settings were used for the study involving the visually impaired in order to take into account the different needs.

The perceptual span is defined as the width of the window of characters used in a fixation to plan the subsequent saccade [4]. Not all the characters in the perceptual span can necessarily be recognized, so the visual span is defined to count the number of recognized characters in a fixation [5,6]. In English, the perceptual span for the normally sighted is 4 characters left of fixation and 15 characters right of it [7], and the visual span is around 10 characters [8]. Forward saccade length is an indirect measure of perceptual span, and was found to decrease from 7.5 letters in control subjects to between 1 and 4 letters in subjects with age-related maculopathy [9]. To compound this issue, the use of magnified text decreases the field of view [10].

For the normally sighted study, the number of pauses per word was set to a constant of 1 as it was assumed that each word could be recognized during this single pause. This is not necessarily a reasonable assumption for subjects with AMD, especially for longer words and for patients requiring larger text size. Therefore, for the partially sighted study, multiple pauses along the length of a single word were allowed.

The number of pauses, p, was primarily determined by the word length, with longer words taking more pauses. To convert between word length and number of pauses a variable of letters-per-pause, w, was introduced. The number of pauses is then the quotient of the number of letters, l, by the letters-per-pause, rounded to the nearest integer, as in equation 5.1. The minimum number of pauses was set to 1.

$$p = \left\| \frac{l}{w} \right\| \tag{5.1}$$

The value of w was chosen according to the font size used by the subject. For smaller font sizes, below about 80, $w = 8$. This effectively meant that, like the settings in the normally sighted study, there was one pause per word. For most participants, $w = 6$, meaning most words had just one pause, but the longest words per paused upon twice.

For the participants using very large font, over around 280, $w = 3$, meaning words 5 letters and longer were paused upon multiple times. The settings were checked with the participant before commencing testing and altered upon their request.

In order to reduce the number of pauses for high frequency long words, a small additive term was also included for words with a frequency, f, above a certain threshold, f_{thresh}. Word frequency is measured according to the logarithmic Zipf scale and was obtained from the SUBTLEX-UK word frequency database for British English [11]. The additive term was linearly scaled to word frequency with a gradient of m and constant of c.

$$p = \begin{cases} \left\| \frac{l}{w} + fm + c \right\|, f \geq f_{thresh} \\ \left\| \frac{l}{w} \right\|, f < f_{thresh} \end{cases} \tag{5.2}$$

The gradient and constant were set such that the maximum size of the additive term, given by the highest frequency word (‘*the’*, $f = f_{max} = 7.67$), would be small compared to the main term; this maximum size was set to -0.2, as in equation 5.3. The additive term should then fall to zero at the frequency threshold, thus the gradient and constant could be calculated according to the simultaneous equations 5.3 and 5.4. The frequency threshold was set to 5.8 on the Zipf scale so that only high frequency words were reduced in pause number. With these settings, $m = -0.085$ and $c = 0.45$.

$$f_{max}m + c = -0.2 \tag{5.3}$$

$$f_{thresh}m + c = 0 \tag{5.4}$$

The viewing position, the position at which the word paused between the arrows, needed to be defined to permit multiple pauses. For words with n pauses, the viewing positions were centrally position in each $1/n$ section of the word. Thus for words with a single pause, the viewing position was set as the centre; for two pause points, viewing positions were at one quarter and three quarter positions; for three pauses points, viewing positions were at one sixth, half and five sixths positions.

In the normally sighted study, the number of pauses was kept constant but the length of each pause was varied. This was decided because the number of fixations and the fixation duration were found to be so highly correlated ($r = 0.97$), as shown previously in Figure

4.9. As some variability is introduced in the pause number in the partially sighted study, it was decided to only vary the pause duration in order to reduce the duration for very high frequency words. Thus words over 6.5 on the Zipf scale were reduced in pause duration by one half.

5.4.3 Text settings

Combined with the dynamic text options, the optimal text characteristics for AMD were researched in the literature. Previous studies have investigated the effects of text size, chromatic contrast, font or typeface, boldness, letter and word spacing. The settings that were found suitable for the majority of people with AMD were used as the default settings. However, a key aspect of our methodology is tailoring to the particular needs of the user. Therefore, for some of the parameters an option was given to the user to tune the default settings for them. This was not possible for all parameters due to the constraints of time with the patients.

One of the most important settings for enhancing reading speed is the text size. A trade-off is required between a size large enough so that it is easily legible, but small enough that it does not decrease field of view [12–14]. The font size was chosen as the critical print size, the minimum text size at which reading speed is at a maximum. After being shown a sample sentence, the participant was given the choice to increase or decrease this size at their preference.

It has been found that a yellow background to black letters was preferred by the majority of AMD subjects, compared to blue, green and red [15]. Therefore, this was provided as an option, along with black letters on a white background and white letters on a black background. Participants were given the choice between the three.

Choice of font or typeface is another consideration. One study found that the Courier font was a better font for reading at font sizes close to reading acuity in AMD, compared to Times New Roman, Arial and Andale Mono [16]. Therefore, Courier was chosen as the font for our study, and no choice was given to participants. A recent study trialled a font specially developed for peripheral vision and found it to improve letter and word recognition in the periphery but not reading speed [17].

The Courier font was set to bold as one of the first participants suggested this was preferable. Subsequently, this option was not offered to other participants. One study was conducted to investigate whether increased boldness increases reading speed in the central or peripheral vision, and found it either remained invariant or, for high levels of boldness, decreased [18].

Letter spacing, word spacing and line spacing are three other parameters of text presentation. Increasing spacing is intended to reduce the effects of crowding, meaning that text or objects close together are difficult to recognise. A study on letter spacing found increasing the spacing did not increase reading speed in central vision loss [19]. A study on word and line spacing found that both double word and double line spacing achieved the highest reading speed in macular disease [20]. However, another study found that line spacing did not improve reading speed in AMD [21]. Standard letter, word and line spacing were used in our study.

5.4.4 Methods

With the text size, colour, font, boldness and letter, word and line spacing fixed, sentences are displayed in one of the dynamic display options: Static (non-dynamic), RSVP, horizontal continuous scrolling (leading or times square), and biomimetic scrolling. The order of dynamic display options was randomised.

In order to minimise any lexical differences between sentences, the sentences from the Radner Reading Chart were used with permission from Wolfgang Radner. The sentences are standardized in terms of their difficulty and syntactical structure, and the number and length of words used [22].

Oral reading speed was the primary outcome measure for assessing the effectiveness of the visual aids. Reading speed using their habitual optical magnifier was then measured using the Radner reading chart. Reading speed was measured at the smallest print size readable with the magnifier without straining (down to a minimum letter size of 0.5 M) as well as at the size above, and the maximum of these speeds used. Participants wore their habitual reading correction (if any).

For the smart glasses, participants wore their habitual distance correction (if any) as the screen is focused at infinity. For the three dynamic text presentation methods, RSVP, continuous scrolling and biomimetic scrolling, the investigator set the speed of text presentation and initiated it. The speed of the first sentence was set to be well below their threshold, with each new sentence increased in speed until the subject was unable to keep up. The maximum reading speed was taken as the speed at which no more than two errors were made.

5.4.5 Results

Through testing the 4 different methods of text presentation, the strategy which enables the fastest reading speed for each individual was discovered. In addition, the individual's preference for the text/background colour and for text size was found. In sum, the size, colour and dynamics of the text on the smart glasses was tailored to the particular needs of the individual.

The reading speed achieved with this tailored approach on the smart glasses is compared, in Figure 5.3, with the reading speed achieved using the optical aid habitually used by the individual. It shows a scatter plot of the reading speed achieved using the optical aid against that achieved with dynamic text on the smart glasses.

Participants 115 and 116 did not bring an optical aid with them to the study as they reported that they did not use one to read. Therefore, their results reading from paper at their critical print size are used instead. Participants 112, 118, 120, 125 and 129 had vision too poor to read from the smart glasses display and thus are not included in this plot.

15 out of 18 participants read faster using the tailored text on the smart glasses than using the optical magnifier. The mean (± standard error) reading speed using the smart glasses was 122 ± 15 wpm and using the optical aid was 74 ± 9 wpm. This is a statistically significant difference as confirmed by a paired-sample t test, $t(17) = -4.61$, $p < 0.001$.

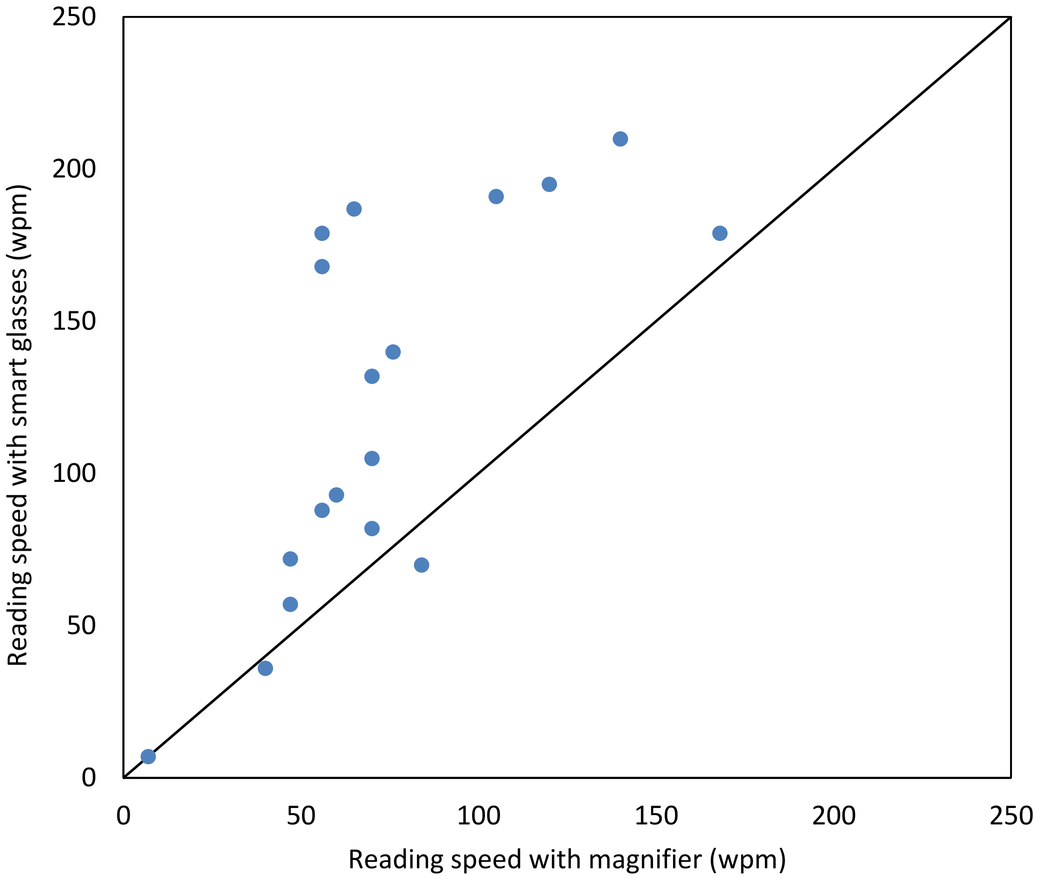

Figure 5.3. Plot of reading speed using optical magnifier against reading speed using dynamic text on smart glasses. The line of equal speed is also plotted, with points above the line indicating a faster speed for the smart glasses.

The four text presentation methods – biomimetic scrolling, continuous scrolling, RSVP and static text – were also compared. It was found that each of the methods enabled the maximum reading speed for a proportion of the participants. Figure 5.4 shows these proportions for each method. This plot is included in order to illustrate the range of preferences across the sample, suggesting that the inclusion of a range of options will assist more individuals than a 'one size fits all' approach. It does not, however, take into account the size of the reading speed differences.

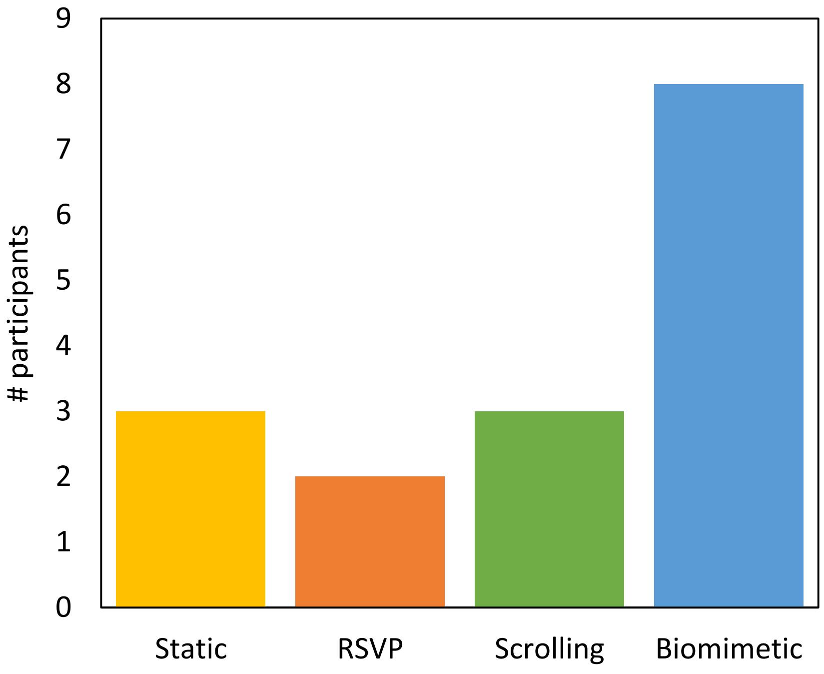

Figure 5.4. Number of participants that achieved their fastest reading speed out of each of the four methods of static, RSVP, horizontal smooth scrolling and biomimetic scrolling.

The mean reading speed for each text presentation method is shown in Figure 5.5. Although biomimetic scrolling has the highest reading speed, the differences between each method are small.

Data were analysed with a linear mixed-effects model (LMEM) with by-subject random intercepts, using the *lmer* programme of the *lme4* package for R [23]. To evaluate the effect of presentation method on reading speed (wpm), we used treatment contrasts in which the RSVP condition served as the reference group. Consequently, the intercept for the fixed effect presentation method estimates the mean value for the RSVP condition. Three additional fixed effects estimate the difference between RSVP and any of the other conditions. For the LMEM we report regression coefficients (b), standard errors (SE) and t-values ($t = b/SE$). A two-tailed criterion ($|t| > 1.96$) was used to determine significance at the alpha level of .05 [24]; effects with $|t| > 1.645$ indicated marginal significance. In the LMEM, the estimated reading speed for RSVP was 95.25 wpm (SE = 13.45, t = 7.08). For biomimetic scrolling, there was a marginally significant increase in reading speed (b = 16.88, SE = 9.31, t = 1.81); specifically, mean reading speed was increased to 112.13 (95.25 + 16.88) wpm. The reading speed for continuous scrolling did not differ significantly from the RSVP condition (b = 8.63, SE = 9.31, t = 0.93). The same was true for the static reading condition (b = 5.44, SE = 9.31, t = 0.58).

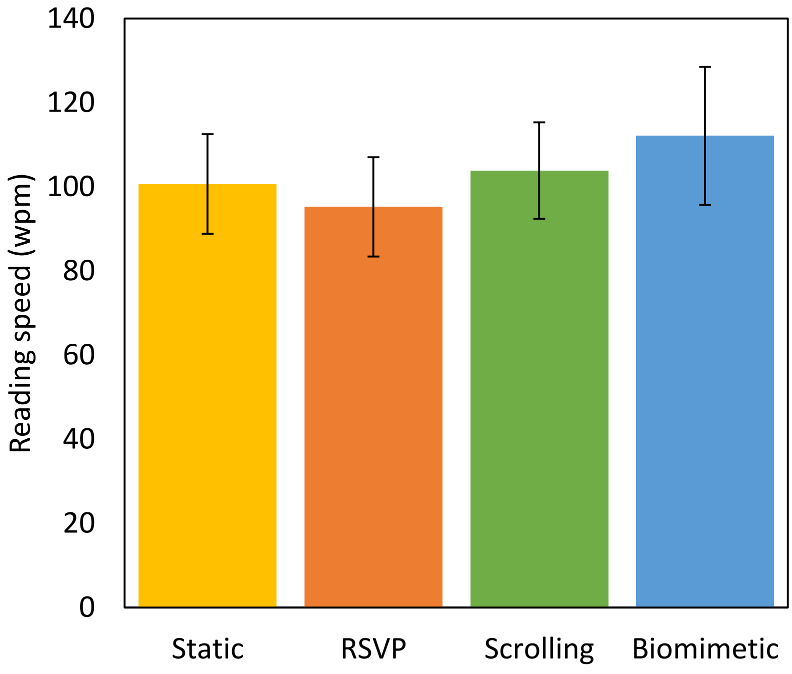

Figure 5.5. Mean reading speed for the four text presentation methods of static, RSVP, horizontal smooth scrolling and biomimetic scrolling.

5.4.6 Questionnaire

At the end of the trial, participants were asked 2 questions. The first was, “Compared to reading large print from paper, did you find reading from the display to be...”, with 5 response options: Much easier, a little easier, the same, a little harder or much harder. The proportion of participants responding to each option are shown in Figure 5.6. The second question was, ‘Did you prefer reading from the display or from paper?’. The responses to this question are shown in Figure 5.7.

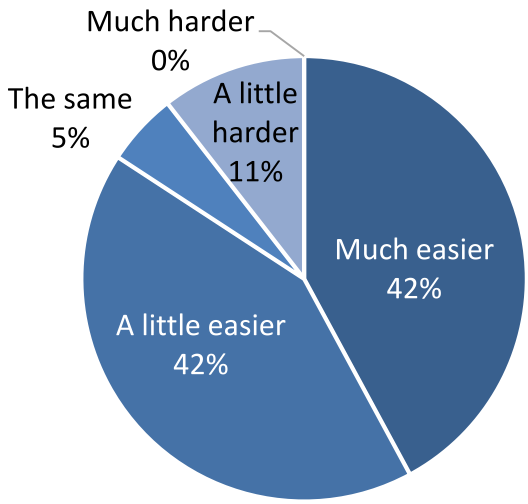

Figure 5.6. Responses to the question, ‘Compared to reading large print from paper, did you find reading from the display to be...’.

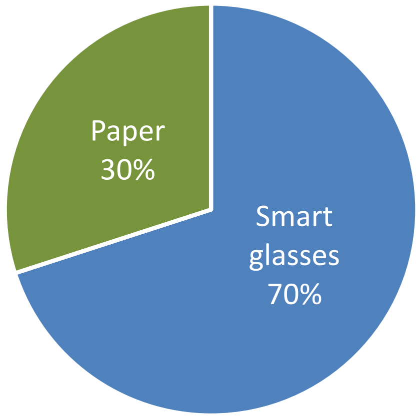

Figure 5.7. Responses to the question, ‘Did you prefer reading from the display or from paper?’

5.5 Jitter

5.5.1 Introduction

In mimicking the movement of the eyes whilst reading, it was stated (in Section 4.3.2) that we used a theoretical model that characterised eye movements as either a fixation or a saccade. For reading, this is a good approximation. In fact, however, the eye is rarely still and during a fixation there are small and irregular saccades. These involuntary movements are termed microsaccades. They occur around 3 to 4 times per second, with a duration of about 25ms and an amplitude usually up to around half a degree [25].

The awareness of the jittering on the retina caused by such movements was the starting point for a study on the visual benefit of inducing image jitter in AMD [26]. This study compared word recognition speed during stationary and jittering conditions in 14 participants with AMD. It was found that, on average, jittering the text increased word recognition speed compared to stationary text, with the effect larger when the sight loss was severe.

Although psychophysically logical, image jitter is usually associated with a degradation in image quality and thus it would seem unintuitive to purposefully induce it. However, as was mentioned in our review paper [3] and in Chapter 2, what may appear an image degradation for the normally sighted can enhance image recognition for the partially sighted.

As some benefit was found to jittering the text, it was decided to incorporate jitter as one of the options available in the text presentation software. In order to test whether inclusion of the jitter option was justified, it was presented to AMD patients. The aim was to find out if jitter was incorporated as an option for text presentation, how many are likely to choose to use it? How many would avoid it?

5.5.2 Implementation

In the study by Watson *et al.* [26] the text was made to jitter between the central position and four other positions at polar angles of 45°, 135°, 225° and 315°. The 0.5° amplitude to this jitter was found to be better than 1°, and inter-jitter intervals of 100 ms or 166 ms had comparable benefits. It was noted that, though the jitter resembles involuntary microsaccades, their implementation of jitter was made with a high frequency and larger amplitude than microsaccades.

In our text presentation software, a switch is included to turn jitter on or off. Jitter amplitude and inter-jitter interval can also be input in the settings screen. For demonstration to study participants, an inter-jitter interval of 100 ms was chosen. The jitter amplitude was 10 pixels which corresponds to 0.15°.

Two types of jitter were implemented: One was 4-way jitter, as proposed by Watson *et al.*, where the text moved in random order between the centre and four positions at polar angles of 45°, 135°, 225° and 315°; the second was a 2-way jitter, where text moved in random order between the centre, directly left and directly right (0° and 180°). The second type was used in demonstration on study participants as this was recommended by an individual with AMD.

In addition, jittering was implemented as a superposition over continuously scrolling text. This idea arose through a conversation with a participant who thought jitter backwards and forwards along the line of movement would be easier to read than 4-way jitter. Whilst the text scrolls across the screen, an instantaneous movement to either the left or the right was made at intervals of 100 ms, with an amplitude of 0.15°.

5.5.3 Results

Figure 5.8 shows the proportion of 12 participants who considered the jitter to either improve or worsen their view of the text, or who had no preference. To a normally-sighted person, the effect of the jitter is quite off-putting – as if the page is being shaken whilst trying to read it. As would be expected, then, those with better eyesight tended to have a similar reaction and quickly discard it, finding the experience quite uncomfortable. However, those who find word recognition a more arduous task did not necessarily dislike it, and the 4 participants who found it better or the same had a reading acuity above 1 logMAR.

As previously stated, our judgement for the value of any one technique is not primarily based on the broadness of its appeal, but by its effectiveness, objective or subjective. This is especially the case for jitter which is immediately off-putting to those with better vision, but may be useful for those with particular visual deficits. Therefore, the fact that one third of the participants were not put off by it suggests that there is scope for its use.

Superimposing jitter over scrolling text has a somewhat less distracting appearance than jitter on its own. Instead of scrolling smoothly, it continuously stutters as it progresses across the screen, jumping forwards and backwards along the axis of movement. This was not part of the main trial; however, it was tested on 3 patients as an additional part. 2 of these achieved the same reading speed in both scrolling and jitter scrolling, but one participant increased in speed from 41 wpm with scrolling to 62 wpm with jitter scrolling.

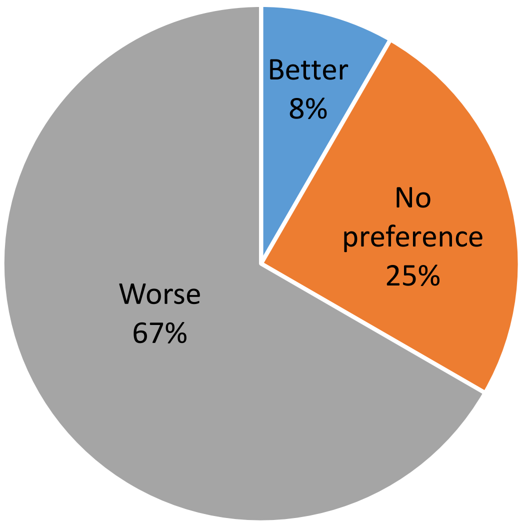

Figure 5.8. Proportion of participants who found jitter improved word recognition, made it worse, or had no effect.

5.6 Stereoscopic display and laptop display

5.6.1 Introduction

One of the unique features of smart glasses over conventional displays is that each eye is presented with its own display screen. This creates a stereo display system and is typically exploited for creating a 3D effect.

For an individual sufferer, macular disease typically progresses at a different rate in each eye, producing an asymmetric difference in eyesight. The ability to control each display screen independently thus opens up the option of tailoring each display screen to that eye.

This left/right difference in eyesight means that individuals with macular disease, like many in the broader population, have a stronger and a weaker eye. Some people will close their weaker eye when reading in order to remove the distraction it causes. Thus one very simple way to use the dual displays of the smart glasses is to shut off the display going to the weaker eye.

The goal is to find out whether, from the patient's perspective, there is any benefit to having independent control over presentation to each eye. Therefore, self-assessment is made by the participants to compare binocular and monocular displays.

This ability to turn off the input to one eye is the only function of the text presentation app unique to the smart glasses. The other functions can be used on any display. Therefore, the subjective views of patients will be sought to compare viewing text presented via the app on the smart glasses screen with text presented on a laptop screen. This will help determine if, in the opinion of individuals with macular disease, any particular advantage or disadvantage is conferred by the screens of the smart glasses.

5.6.2 Implementation

The Epson Moverio BT-200 supports side-by-side 3D format in which the left hand screen displays the left hand side of the display, and the right screen the right hand side. Therefore, a stereo version of the software has been developed which displays the text in side-by-side format. Care was taken to align the text correctly such that, on the smart glasses, the visual input from the right and left eyes merged into a single image.

Three configurations were used: Dual display, in which text was displayed on both screens; right hand screen only, where text was only displayed on the right screen and the left screen was blackened; and left hand screen only.

Participants were initially shown a word in dual display, then right screen only and left screen only were shown in turn, switching back and forth to compare among them. They were not informed of the screens configuration. The participants were asked to compare the text and say when they could see it better. Usually one of the participant's eyes was worse, and so the option of displaying to the worse eye only was quickly discarded as the worst option. Then they would compare between dual display and display to the best eye only.

The participants were also asked to compare between the smart glasses and a laptop display. The laptop used was a Fujitsu Lifebook AH532, with 15.6-inch LCD display with average brightness 174 cd/m^2. The text was shown in the same format on both displays and participants were asked the question, 'Which can you see better? The laptop screen or the smart glasses screen?'

5.6.3 Results

19 participants were asked for their preference between reading text that was displayed on both screens to both eyes, to text displayed only to their best eye. Figure 5.9 shows the proportion of responses to either having dual display, single display or no preference.

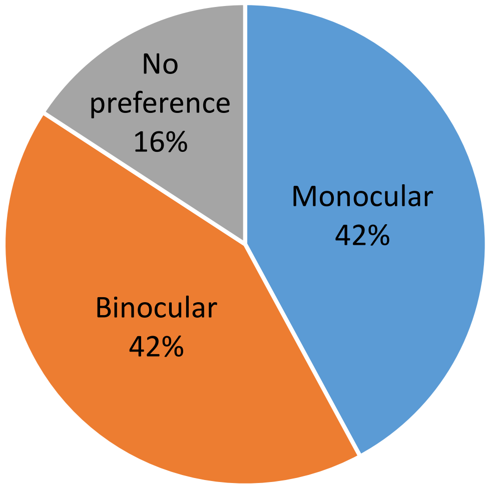

Figure 5.9. Proportion of participants who stated a preference for binocular (dual display to both eyes) or monocular (single display to their best eye) presentation, or who stated no preference.

19 participants were asked to compare the smart glasses screen with the laptop screen for reading text. Figure 5.10 shows the distribution of responses that indicated a preference to one or other display, or which considered them equal. Of the 6 who stated a preference for the laptop, 2 explained that this was due to the movement of the smart glasses screen moving with their head. The reason cited by another 2 participants was due to them being able to use their own techniques for reading; for one this was going up very close to the screen, for the other it was the ability to use head-movements while reading. Of the 7 who stated a preference for the smart glasses, 3 commented on it being much clearer to read from than the laptop, with one of these stating that there was glare on the laptop screen. Another gave the reason that they could sit up with the smart glasses.

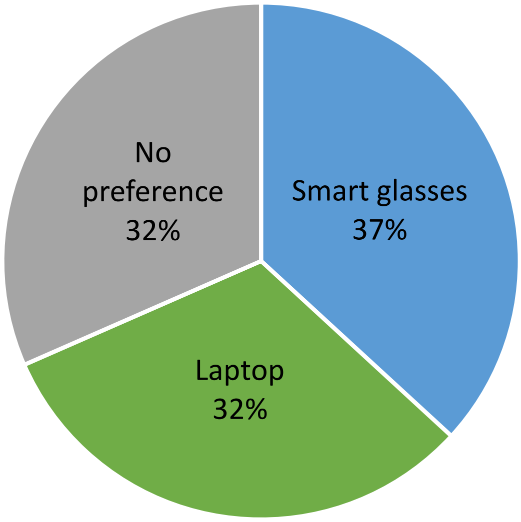

Figure 5.10. Proportion of participants who stated a preference for the smart glasses screen or the laptop screen, or those with no preference.

5.7 Discussion

5.7.1 Reading aid

Tailored text presentation on the smart glasses was found to enable a faster reading speed than the optical magnifiers habitually used by the participants. The average increase was a statistically significant 64%, with 15 of 18 experiencing an increase. This is an encouraging result which offers some evidence that this approach to assisting reading in macular disease is effective.

However, the purpose of the study was primarily to assist with the development process, rather than as a thorough test of a finished product. More thorough testing is needed in order to make a more definitive assertion about the effectiveness of the smart glasses in aiding reading and how they compare to optical magnifiers. One limitation of the evidence is that only the reading of single sentences was tested, whereas a more extended reading test would simulate normal reading more closely. Also, an increase in precision would have been achieved if more sentences had been tested close to threshold. However, it was decided to prioritise testing a range of methods in the limited contact time with the patients.

Given that the optical magnifier was habitually used by the participants, and in most cases prescribed by the low vision clinic, they were generally well familiar with its use. By contrast, the smart glasses were new to all participants save the four participants who had participated in the pilot trial. Just 9 of 23 had ever used any electronic low vision aid. This comparative lack of experience does not seem to have limited the benefit of this new technology, but the effect of familiarity or practice needs to be investigated.

In order to tailor the text to the large range of visual deficits present in a group of individuals with macular disease, a large range of choices for tailoring are needed. This was justified by the fact that all four of the dynamic presentation methods, biomimetic scrolling, continuous scrolling, RSVP and static, enabled the fastest reading speed in at least two of the participants. Although biomimetic scrolling was the best for the largest number, software for enhancing reading would benefit from the inclusion of every method.

The self-assessment of users matches the objective measures, with 84% finding it easier to read using the smart glasses than reading from paper. This corresponds to the preferences expressed by participants, 70% of whom preferred reading from the smart glasses than from paper. In their assessment, several participants referred to the clarity of the display. Others, however, pointed out one of the key differences between displays that are head-mounted and those that are not, namely, that head movements cannot be used to look across the display; eye movements alone must be used. For the participants who relied heavily on head-movements, this was a problem. The dynamic presentation of text removes the need for either eye or head movements, so most participants did not express an issue with this.

5.7.2 Biomimetic scrolling

For normally sighted participants, there was no statistically significant difference between the two speed reading strategies of RSVP and biomimetic scrolling, as reported in Chapter 4. However, there was a marginally significant increase in reading speed using biomimetic scrolling for the participants with macular disease.

One difference between the normally sighted and partially sighted studies concerned practice. For the normally sighted study, practice was gained while reading at lower speeds, and participants were thus prepared when the speed was incrementally increased to high speeds. Therefore, when reading near threshold, participants had typically already read over 12 sentences. For those with the most severely impaired vision, even the slow speeds are a struggle to read and so less practice was gained before reaching threshold.

Previous studies to compare continuous scrolling and RSVP have demonstrated the challenge posed in comparing reading with different strategies in a low vision population. For example, one study found no difference in reading speed [27] before a subsequent study found a difference at a larger text size [28]. Thus further studies are required to comprehensively compare biomimetic scrolling with other methods.

The parameters involved in defining the dynamics of text movement in biomimetic scrolling were described in Chapter 4. There are many different ways in which these parameters can be configured, and their settings for use on a low vision population were presented in Section 5.4.2. As contact time with patients was limited, the choice over these settings was chosen through reference to the documented knowledge about the visual limitations of macular disease. For example, it was decided to allow multiple pauses per word due to the reduced perceptual span caused by macular degeneration.

However, the choice to evenly distribute these pause points across the word reduced the resemblance of the text movement to natural movements because refixations are not necessarily distributed in such a way. Whether or not this affected reading speed is unknown. Several configurations of biomimetic scrolling parameters need to be further tested in order to refine them and measure their respective effects on reading speed.

It may also be possible to set the parameters based on the individual reading performance of an individual. Cheong *et al.* defined the information transfer rate in bits per second as the size of the visual span in bits divided by the exposure time in seconds [29]. This ranged from as low as 9.34 bit/s to as high as 406.2 bit/s (the median for normal vision was 407.7 bits/s) in the 13 subjects with AMD that they tested. Information transfer rate (but not visual span) was found to be significantly correlated with reading speed. Therefore, information transfer rate could also be used in deciding the parameters for biomimetic scrolling.

5.7.3 Jitter and peripheral word recognition

A major limitation of the feedback gained on jitter is that it only tested the participants' first impression. This does not allow for any perceptual adaptation to the effect. In addition, word recognition improvement could be conferred by jitter without a subjective preference. Nevertheless, if there is a subjective dislike for the effect then it is unlikely it would be used.

Besides the spatial modulations of jitter, modulating other parameters of the text has also been investigated and these could be incorporated as options in the text presentation app. These generally have been considered for their effect on word recognition in the peripheral vision. In addition, they look at their benefit for reducing the effects of crowding, and the increase in difficulty created by the proximity of other objects.

Jiggling, an effect similar to (if not identical to) jitter, is defined in one paper as "rapid displacement along a specified direction with a fixed magnitude, repeated at a given temporal frequency" [30]. This paper found an increase in letter recognition in the periphery when motion was applied to the letters. This effect was also observed for zooming motion [31]. Another effect is temporal modulation, such as a moving window in which component letters are sequentially presented. One study found that the spatial extent of crowding was reduced when this effect was applied [32]. Contrast modulation is another effect that may be beneficial [33].

The influence of each of these effects on reading with macular disease needs to be investigated. As with jitter, the effects would be considered useful and worthy of inclusion in the text presentation app if they are shown beneficial to any number of low vision subjects, even if there is no average improvement amongst a population.

5.7.4 Fixation target

The text presentation app includes both screen visibility tests and text tailoring and presentation functionality. These two components, respectively relating to the assessment and assistance of vision, are closely connected. One example of how they interrelate was given in Section 5.3.1: The 'extent of visibility' test maps out the visible areas of the screen relative to the centre point, which then leads to a fixation target being appropriately positioned on the text presentation screen to act as an aid to using the PRL. Though this was presented to two patients, training is normally required to introduce a new method of eccentric viewing. Further work is needed to investigate whether this can be used in training courses for eccentric viewing.

If a fixation target were used, a suggestion by Déruaz *et al.* could be investigated [34]. They looked at fixation instability, whether alternating the point of fixation between two points 10° apart could improve text perception during eccentric viewing. The participants reported that the letters were refreshed for about 1 second after alternation but that there was a rapid fading effect during persistent fixation.

5.8 Conclusion

A system of text presentation, optimised to the needs of the user, and displayed on smart glasses, was implemented and trialled on patients. The average reading speed using the smart glasses system was found to be higher than using a habitual optical magnifier. Four methods of dynamic text display, including biomimetic scrolling, were implemented and compared. Though biomimetic scrolling enabled the fastest reading speed for the most participants, all four methods were needed to achieve maximum speed in all participants. Additional features, jitter and stereoscopic display, were also demonstrated to participants for initial feedback, and a minority responded positively to each. Subjective preference to the smart glasses system was high, both in terms of self-assessed ease of reading and preference compared to reading from paper.

5.9 References

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CHAPTER 6

Conclusion

6.1 Conclusions

This research project set out to aid the reading performance of individuals with macular disease in two interrelated ways: The first was to investigate the benefit, if any, of the head-mounted display system; the second was to individually tailor the presentation of text on this platform, particularly making use of dynamic text display.

The concept of the screen visibility test was introduced as a way to measure the visibility of displays to partially sighted users. Based on standard vision tests, three screen visibility tests were developed for head-mounted displays to indicate the level of contrast and the extent of the screen visible, and reading performance from the screen.

According to the 'extent of visibility' test, the model of smart glasses tested was at least 45% visible to 6 out of 8 participants with macular disease, and to 6 out of 7 participants for the smartphone headset. The two participants who failed to see this proportion of the screen were both registered blind, with reading acuities worse than 1.6 logRAD. Furthermore, one of these participants failed to read from either display, whereas all other participants succeeded in reading from both. It was thus concluded that these displays are accessible to a large proportion of those with macular disease.

A novel approach to dynamic text presentation was introduced, termed biomimetic scrolling due to its mimicking of natural eye movements. Normally sighted participants were able to read text moved with biomimetic scrolling at almost 5 times the rate of continuously scrolled text. This increase was attributed to the removal of the need for users to make saccades, as is the case for RSVP which was read at the same speed as biomimetic scrolling.

Biomimetic scrolling was also found to be the method of text presentation most likely to enable the fastest reading speed in individuals with macular disease, though the averages across the sample population for the four methods were similar. The test was optimally tailored to each individual with the fastest dynamic text display method and the preferred font size and colour. This optimally presented text on the smart glasses was found to increase reading speed over the habitually used optical magnifier in 15 out 18 participants, and by an average of 65%.

User acceptance of the smart glasses was also high, with 84% of participants finding it easier to read from the smart glasses than from paper and 70% preferring it. In comparison to a laptop screen, participants were almost evenly split in declaring a preference for the smart glasses screen, the laptop screen or no preference. Jitter and monocular display had some appeal to a minority of participants.

6.2 Further research

6.2.1 Biomimetic scrolling

Biomimetic scrolling is, to the best of our knowledge, the first reported attempt to translate natural eye movement into a text presentation strategy that mimics the natural movements of the eye whilst reading. The scheme for achieving this was described by outlining the text movement parameters that are equivalent to the eye movement parameters. Four ways to programme text movement according to eye movement were suggested: Reverse engineering the eye movements of an individual is the closest mimic; using average values of a population, moderated by a speed control, smooths over anomalies but requires eye tracking data for the sentences being scrolled; using trends between word frequency/length and fixations/saccades can be used for any text; data on visual impairments can also be used to set appropriate parameters.

Two configurations of biomimetic scrolling were trialled – one for normally sighted participants and one for participants with macular disease. Both contained a speed control, and the latter additionally included a letters-per-pause control. More configurations would need to be trialled to determine the optimal settings. The effects on reading comprehension would also need to be measured in addition to reading speed.

In its current form (irrespective of any further optimisation), the core functionality of a biomimetic scrolling app has been written. This is equally relevant to both normally and partially sighted individuals. All that is required is to make it user friendly in terms of text input and control, then to package it for an operating system. Further consideration would also be needed for its use on larger blocks of text, as it has primarily been used for single sentences.

Another potential application of biomimetic scrolling is as a training device to improve reading in macular disease. RSVP [1] and continuous scrolling [2] have both found some success in this capacity. But because biomimetic scrolling intentionally aims to mimic natural reading patterns it may confer a particular benefit in this regard. For example, reading speed correlates with the size of forward saccades for individuals with central field loss [3,4]. Further, the effect of forward saccade size on reading speed was found to be mediated by the total number of fixations and not by the average fixation duration [5].

In light of this, a training regime for an individual with macular disease could follow the following steps:

1. Use eye tracking to measure the average size of forward saccades
2. Programme biomimetic scrolling with the average distance between pauses equal to the average size of forward saccades
3. Steadily increase the distance between pauses to train in reading with larger saccades

Eye trackers are not usually thought of as consumer products due to their prohibitively high cost. However, consumer class eye trackers are becoming more readily available, such as those sold by The Eye Tribe. The use of a consumer class eye tracker in such a training regime would need to be investigated to assess its effectiveness.

6.2.2 Additional features

All major operating systems now come with built-in accessibility functionality which, for visual impairments, typically includes zoom, colour inversion and text-to-speech. These are each activated and deactivated through the user input. A suggestion for enhancing the accessibility function is to run an optimisation process which inputs the visual condition of the user through screen visibility tests, characterises the needs of the user for viewing the display, and presents content accordingly. The suggestion of using the 'extent of visibility' test to position a fixation target, described in Section 5.7.4, is an example of this process.

Information about the eyesight of the user can also be gained through monitoring their reading characteristics. Whilst using biomimetic scrolling, for example, the speed of scrolling and text size used can be recorded over time to monitor change. A reading test, such as that used in this thesis, can confirm such a change. This could act as an early warning system for users, identifying a possible change in their vision.

There was limited appeal for jitter and for the independent control over each display. Further research is needed to determine whether spatial, contrast or temporal modulations of the text can benefit certain individuals, most likely those with significant impairments. Shutting off the display to the weaker eye was trialled, but it is possible that the individual optimisation of the displays to each eye could assist even further.

6.2.3 Towards a useable system

A novel reading aid has been described in this thesis, providing a range of options to ease the process of reading for a range of visual deficits and making use of recently developed smart glasses. During the trials, the device was operated by the experimenter in order to focus testing on the visual benefits. In a real life scenario, the device would be operated by the user in environments outside the clinical setting, for a range of tasks. Some suggestions for user control were made in Sections 5.3.2 and 5.3.3, regarding the input and control of text. A prototype device needs to get into the hands of the end user in their home environment to take the development process further. This would also allow a more extended trial period for lengthier reading tasks to be tested, and any possible side-effects to be picked up.

Chapter 3 considered two kinds of head-mounted display, the smart glasses and the smartphone based headset. The large, bright screen of the smartphone while encased within the headset was found to be quite beneficial to participants. The smart glasses were chosen for further investigation over the smartphone headset. However, due to the prevalence of smartphones, they present a budget option compared to the niche smart glasses product. Using a simple phone-mount and appropriate lenses, such as the Homido headset used in Chapter 3, any smartphone could be used.

The methods presented here are not restricted to one or two devices or display types. Real life trials could be carried out for the software only, utilising the displays already available to users, such as personal computers, tablets or smartphones. Television screens could also be used via screen sharing or an HDMI or VGA connection. The app would need to be packaged for the requisite operating system. One reason Kivy, an open source Python library, was used to build the app is because it runs on Linux, Windows, OS X, Android and iOS, and is free for commercial use.

6.3 Potential impact

Almost 2 million people in the UK live with sight loss that has a significant impact on their daily lives [6]. This is projected to double in the next 25 years [6]. For most of these, their condition is incurable. They are thus reliant on visual aids to make the most of their residual vision. The reading aid described in this thesis has the potential to expand the range of available low vision aids which is hoped to have a positive impact on people's lives.

Many individuals with sight loss also suffer from comorbidities. For those with impaired motor skills, a head-mounted device could be particularly beneficial. Normally sighted users may also find the biomimetic scrolling technique useful. Not only does it increase speed but may also increase focus. For those with difficulties in reading, such as dyslexia, an alternative form of text presentation may also be useful.

The process for commercialising the outputs of this thesis have already begun. A patent application has been filed to protect biomimetic scrolling (Patent Application number 1615382.7, 9th September 2016). An application is being prepared for the Confidence in Concept scheme of the Medical Research Council to fund the further research suggested in this thesis. A biomimetic scrolling app is being developed for release. Furthermore, at least 3 other groups that are developing smart glasses for the visually impaired have already used the published review paper to inform their work.

I believe the approaches described in this thesis have the potential to enhance the reading experience of many people, and to this end will the work continue.

6.4 References

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